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STUDY OF NAVAL AIR STATION OPERATIONS TO REDUCE FUEL CONSUMPTION

by

Adam V. Gable

June 2014

Thesis Advisor: Roberto Szechtman
Second Reader: Michael Dixon

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13. ABSTRACT (maximum 200 words)

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In this thesis, we model ground operations at Naval Air Station (NAS) Oceana and NAS Lemoore to identify and reduce the time an aircraft spends with engines online during post-flight operations. Specifically, by reducing the processes performed while conducting hot brake checks and reducing resources required at the hot skids, we are able to save over $8 million at NAS Oceana and Lemoore alone. In addition, we have identified zero-cost coordination efforts that increase synchronization of fuel truck delivery to their consumers, such as noting refueling intentions on schedules to allow fuel truck managers to allocate trucks more efficiently, leading to additional savings. We provide recommendations specific to each base and recommendations that can be adopted fleet-wide. Finally, we identify that the current allocation of aircraft among bases is suboptimal and provide policy recommendations that would improve overall readiness.

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STUDY OF NAVAL AIR STATION OPERATIONS TO REDUCE FUEL CONSUMPTION

Adam V. Gable
Major, United States Marine Corps
B.S., The Ohio State University, 2002

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June 2014

Author: Adam V. Gable

Approved by: Roberto Szechtman
Thesis Advisor

Michael Dixon
Second Reader

Robert Dell
Chair, Department of Operations Research

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LIST OF ACRONYMS AND ABBREVIATIONS

AAR	aircraft arrival rate
Air ENCON	Aviation Energy Conservation Program
ATC	Air Traffic Control
ATCM	Air Traffic Control Management
ATCSCC	Air Traffic Control System Command Center
CATM-9	captive air training missile
CDM	Collaborative Decision Making Program
CI	confidence interval
CNO	Chief of Naval Operations
CR	Collaborative Routing Program
CSFWA	Commander, Strike Fighter Wing, U.S. Atlantic Fleet
CSFWP	Commander, Strike Fighter Wing, U.S. Pacific Fleet
DLL	dynamic-link library
DOD	Department of Defense
DTS	date time stamp
F/A-18	fighter and/or attack aircraft
FAA	Federal Aviation Administration
FCLP	field carrier landing practice
FRS	Fleet Replacement Squadron
GAMS	General Algebraic Modeling System
GDP	Ground Delay Program
G/G/s	multi-server queue with general interarrival and service time distributions
gmp	gallons per minute
GUI	graphic user interface
ISIS	Integrated Shipboard Information System
mm:ss	time presented in minutes and seconds
mph	miles per hour
NAE	Naval Aviation Enterprise
NAS	Naval Air Station
ppm	pounds per minute

rft	ready for tasking
SHARP	Sierra Hotel Aviation Readiness Program
Simio	Simulation Modeling Framework Based on Intelligent Objects
SME	subject matter expert
VBA	Microsoft Excel Visual Basic for Applications macros
VFA-106	Strike Fighter Squadron 106
VFA-122	Strike Fighter Squadron 122

EXECUTIVE SUMMARY

With over 3,700 aircraft burning over 600 million gallons of gas a year, naval aviation accounts for 54% of all naval fuel consumption. Naval aviation is the second largest consumer of fuel in the Department of Defense, Air Force aviation being number one. Over the next two years, legacy F/A-18 C/D hornets will be replaced by the 28% larger F/A-18 E/F super hornets, burning 26% more fuel. As our aircraft are getting larger, our defense budget is getting smaller. By 2017, the defense budget is expected to reduce by 20%. Sequestration would further reduce the defense budget by $50 billion each year through 2021.

Recognizing these challenges, the Chief of Naval Operations (CNO) established the Aviation Energy Conservation Program (Air ENCON) to act as the lead organization responsible for spearheading fuel management initiatives the naval aviation enterprise. Air ENCON has set a benchmark of achieving a “4% reduction in non-mission fuel burn in aviation by 2020 without adversely affecting mission execution or safety.” Air ENCON has already established energy management as a mandatory Commanding Officer Fitness Report and Counseling Record element. They are currently conducting a beta test program on quarterly squadron “energy report cards” (Air ENCON, 2013).

However, there are still many inefficiencies that can be improved upon at zero cost. Many process improvements have been identified but few have trickled up the chain to become fleet-wide recommendations. This occurs due to a few reasons; squadrons either do not know how to pass the information up the chain, there is no data to support their claims, or process improvements are low on their priority list because of the demanding squadron schedule. Our goal in this thesis is to find squadron-level efficiencies and bridge the gap between tactical and institution-wide recommendations. By taking improvements found at a tactical level and examining them with a “Big Navy” lens we are able to determine if institutional-level best practices can be implanted, in turn improving not just one or two squadrons but the entire Naval Aviation Enterprise (NAE). In order not to detract from mission execution or safety, we focus on identifying fuel savings through ground process improvements. To that end, we have created a model that simulates daily flight operations at the Navy's two largest airbases, Naval Air Station (NAS) Oceana and NAS Lemoore. We use data collected by Commander Strike Fighter Wing Pacific (CSFWP) and staff, Commanding Officer Strike Fighter Wing Atlantic (CSFWA) and staff, training squadrons VFA-106 and VFA-122, and both bases' Fuels Division Managers, Air Traffic Control Officer/Chief, and Supply Officers.

Our objective is to identify bottlenecks in ground operations that are either shared among bases or base-specific, find ways to streamline those processes, and make fleet-wide policy recommendations and base-specific recommendations based on our findings. Our simulation is done through a highly parameterized, flexible model using an easily adjustable Microsoft Excel user interface to allow users to experiment without having to redesign the main skeletal structure in the simulation software. Our recommendations have no adverse effect on readiness, proficiency or flight operations.

While NAS Oceana and Lemoore differ in location and composition of critical infrastructure, they (and all Navy fighter bases) share a common set of procedures that an aircraft must route through. Upon landing, each aircraft must route through the hot brake check, where a squadron maintainer checks to ensure the brakes aren't overheating. Additional checks are often done at this time as well, such as degaussing the aircraft from static electricity by wiping a grounded cloth across the canopy, and covering the seeker head of captive missiles such as the CATM-9. Following hot brake checks, the aircraft either routes to a hot skids refueling location or to processes in the squadron line area, depending on how long the aircraft has until its next departure. If time to next departure, or turnaround time, is less than 60 minutes, the aircraft must refuel at the hot skids. Hot skid refueling occurs with the engines on and requires a crew of four maintainers. At Lemoore, hot skids also require a fuel truck driver to operate a safety shutoff switch called the "dead" switch. This not only pulls a fuel truck driver from his primary duty but also takes a fuel truck out of operation because the driver parks the truck during the refueling evolution. Following hot skids refueling, the aircraft routes to the squadron line to conduct additional processes in preparation for the next launch. If turnaround time is greater than 60 minutes, aircraft generally proceed directly from the hot brake check to the squadron line, where the aircraft conducts post flight checks and then shuts the engines down. Following engine shutdown, a fuel truck refuels the aircraft.

We model refueling processes along with all other applicable ground processes in our simulation. We drive the model using four weeks of empirical flight schedules collected at Oceana and Lemoore to determine our baseline metric of average ground idle time per aircraft, 25:24 (mm:ss) $\pm$ 35 seconds with 95% confidence interval (CI) at Oceana, and 21:12 $\pm$ 22 seconds with 95% confidence at Lemoore. Through our analysis we determined that approximately two thirds of all the delays occur in processes conducted outside of the squadron line area, specifically at the hot brake checks and hot skids refueling. At Oceana 41% of delay time occurs in the hot brake check queue, and 32% occur at the hot skids queue. At Lemoore 54% occur in hot skids queue and 28% in hot brake queue. Next, we experiment with potential ground process improvements discovered through our data collection efforts.

We found statistically significant reductions in average idle time by adopting eight policy recommendations. The first two recommendations involve the hot brake check. Two procedures that often occur in the hot brake check can be moved to the squadron line; those are degaussing the aircraft and covering the CATM-9 seeker head. Degaussing must occur prior to the aircrew exiting the aircraft and therefore can be conducted in the post flight process area in the squadron line. Covering the CATM-9 seeker head at the hot brake check area is a carryover technique from when CATM-9's had a safety switch that was required to be safed immediately after landing. The current CATM-9 version no longer has this switch and this task can therefore be moved to the squadron line area as well.

The third recommendation is to utilize a laser gun to check brake temperature rather than using the back of hand technique. The laser gun is not only quicker and more efficient, it is also safer. By implementing these three policy recommendations, we estimate a 72 $\pm$ 42 second reduction in average idle time with 95% confidence at Oceana, and a 30 $\pm$ 21 second reduction in average idle time with 95% confidence at Lemoore.

Policy recommendations four through six increase the quantity and quality of information being passed from squadrons to the fuels division. Recommendations four and five are very simple; always refuel the last flight with fuel trucks and be vigilant in making 10 minute out calls at 10 minutes out. Turnaround time is not critical for the last wave of aircraft returning to base and, when given prior notice, fuel trucks have ample opportunity to refuel prior to the next day's events. The 10 minute out call is the radio call from the inbound aircrew to the squadrons' maintenance control. Maintenance control then relays the message to fuels division, which then dispatches a truck. The call is intended to be initiated 10 minutes prior to when the aircraft is expected to be shut down in the line. However, aircrew often make this call early, late, or fail to make it at all, leading to inefficiencies in fuel truck operations and unnecessary delays.

Policy recommendation six is to annotate known hot skid turnarounds by marking "HS" in the notes section of the flight schedule. Squadrons typically know when particular flights are going to require hot skid refueling, but there is no indication of such evolutions on any documents given to the fuels division. Currently, the fuels division at Oceana and Lemoore receive a fax or e-mail of the compiled squadrons' schedules the night before execution. If fuels division managers were given an indication on which flights would require a fuel truck and which time periods would be busiest, they could allocate drivers more efficiently and even preposition trucks.

We experiment with a smarter fuel truck routing process that assumes the fuels division has increased awareness of refueling intentions and a higher quality of information. Our results indicate that by increasing the quantity and quality of information provided to the fuels division, we are able to reduce average idle time by 6 ± 30 seconds with 95% confidence at Oceana and 24 ± 21 seconds with 95% confidence at Lemoore.

Our seventh policy recommendation involves operations specific to Lemoore. We recommend that squadron maintainers be allowed to operate the “dead” switch at the hot skids in order to prevent aircraft from having to wait at the hot skids for a fuel truck driver to arrive. This policy also frees the fuels truck driver to service more aircraft. We experiment with a policy change of allowing squadron maintainers to operate the “dead” switch by removing the requirement of a fuel truck for hot skid operation. We determine that the new policy would reduce average idle time by 48 ± 38 seconds with 95% confidence at Lemoore.

Finally, our eighth recommendation is to organize periodic detachments (det’s) of aircraft and instructor pilots from VFA-106 (located in Oceana) to VFA-122 (located in Lemoore). With a small det of aircraft we are able to increase the production capabilities at Lemoore without affecting training requirements at Oceana. Det’s have side benefits of increasing standardization of training, reducing the standard deviation of time to train, and decreasing the number of warm-up flights required due to lack of aircraft. Through analysis of student production requirements, aircraft allotment and ready for tasking (rft) rates, we estimate a det of 2–4 aircraft for a two-week period will increase the sortie rate at Lemoore without decreasing the rate at Oceana. The det also reduces overall percentage of hot skids refueling by 5.7%. In order to avoid the flaw of linear thinking, this policy should be readdressed periodically as rft rates and student loading change over time.

In our simulations, combining all of our policy recommendations reduces average idle time by 78 ± 40 seconds with 95% confidence at Oceana and 72 ± 24 seconds with 95% confidence at Lemoore. If adopted, we estimate our eight recommendations would reduce fuel consumption by 250,920 gallons of gas, saving the Navy over $8 million in fuel and maintenance costs per year at Oceana and Lemoore alone.

Finally, we conclude with an investigation into a policy requiring aircraft to shut off an engine after safely exiting the runway. We assume that aircraft burn fuel at the same rate while taxiing regardless of how many engines are online because the same thrust is required to create acceleration. The true cost savings occur when the aircraft is static either in a queue or conducting post-flight procedures, which accounts for 66% and 67% of ground time at Oceana and Lemoore, respectively. By incorporating a single engine policy, we are able to reduce fuel consumption by over 1.5 million gallons, saving the Navy over $50 million per year. If adopted across all fighter bases, savings would be substantially higher.

I. INTRODUCTION

The Department of Defense (DOD) is pursuing a comprehensive energy policy to align with national-level energy guidance. The Deputy Secretary of Defense is spearheading an effort to institutionalize energy priorities across the full range of military activities, including operational and facilities energy. As policy is finalized, the Secretary has issued interim guidance to “adapt core business processes—including requirements, acquisition, planning, programming, budgeting, mission assurance, operations, and training—to improve the Department’s use and management of energy” (Posner, 2013). Rather than a one-time fix, the DOD’s policy will be thorough and comprehensive, covering all aspects of military operations.

The Navy currently uses 28% of all DOD Energy, and naval aviation accounts for 54% of that total. Expressed differently, naval aviation accounts for 15% of all DOD fuel consumed (Schwartz, Blakeley & O’Rourke, 2012). With every $1 increase in the price of fuel, the Navy pays an extra $31 million annually. Not surprisingly, energy initiatives developed by the CNO have been established to target the most fuel-intensive portions of naval operations. In 2010, the CNO signed the Navy Energy Vision, setting goals for the Navy to:

- Value energy as a strategic resource
- Understand how energy security is vital to executing the Navy’s mission
- Be resiliant to any future energy challenge

Task Force Energy was established to identify initiatives that promote energy efficiency afloat and ashore. The Naval Aviation Energy Conservation (Air ENCON) Program is the aviation arm in charge of identifying fuel reduction opportunities by naval aviation units in ground operations, flight operations, sea-based and shore-based operations (Air ENCON, 2014).

The goal of this thesis is to provide senior leadership with practical, effective, and flexible methods to reduce fuel consumption without affecting operational readiness, pilot proficiency, or safety through the use of a generalizable simulation tool. We utilize Simio simulation software, a discrete event-driven simulation software package. Our simulation model consists of three parts:

(1) Architectures of two base models, Naval Air Station (NAS) Oceana and NAS Lemoore, are built utilizing data collected from the staffs of Commander Strike Fighter Wing Atlantic (CSFWA), Commander Strike Fighter Wing Pacific (CSFWP), Air Traffic Control, Air Operations, Fuels Manager, Supply Officers, and Training Squadron Operations Officers (VFA-106 and VFA-122). We chose these two bases based on the fact that they are they Navy’s two largest air installations. By modeling across bases we are able to analyze policy decisions at a macro level. Previous research that has helped frame our model logic is introduced in Chapter II.

(2) A Microsoft Excel graphic user interface (GUI) is created that allows non-analysts the ability to modify parameters and experiment with schedules without having to redesign the main skeletal structure in Simio. The GUI allows non-Simio users to conduct their own experiments and sensitivy analysis on potential cost savings policies. We add the capability to bind excel to Simio by adding user-defined dynamic-link library (DLL) file extensions to the Simio program file. The DLL populates user-defined “ExcelConnect” elements which we leverage to import Excel spreadsheets into Simio data tables. The models process logic is driven by the content of the tables. This method leads to the ability to build models of scale and complexity that are limited only by the user. Properties such as aircraft type, fuel burn rate, number of aircraft, number of squadrons, number of fuel trucks, and delay time in post flight processes are all manipulated in Excel. Aircraft are routed through the model according to the squadron schedules in Excel. We outline the models and Excel interface in Chapter III.

(3) Experiments are created to analyze the effects of potential process improvements. By visiting with leaders at both Oceana and Lemoore, we were able to identify several areas in post-flight operations where policy changes could have a significant impact on reducing delay time in queues. We experiment with these policy changes and present our results in Chapter IV. We conclude with our recommendations in Chapter V.

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II. LITERATURE REVIEW

In literature review we introduce research that has contributed to our baseline knowledge of airport operations and aircraft scheduling and research that has helped frame our model logic. Four specific research fields are discussed in this section; commercial airline scheduling, federal aviation administration (FAA) programs, healthcare queuing models, and DOD aviation energy conservation.

A. COMMERCIAL AIRLINE SCHEDULING

The Bureau of Transportation Statistics states that in 2013, 7.79% of delays were caused by late arrivals, up from 6.58% in 2009 (Research and Innovation Technology Administration, 2014). According to Airlines for America, the U.S. airline industry experienced a total of $7.18 billion in delay costs in 2013 at an average cost per minute of $78.17 (Airlines for America, 2014). Such costs are prompting airlines to shift focus to address the expected cost of operations incorporating some level of uncertainty. The DOD can benefit from research conducted in this area, particularly in flight delay propagation, airport and airline schedule robustness, and cost saving through optimization of resource scheduling.

Kondo, AhmadBeygi, and Cohn identify that much of the academic research conducted on the commercial airline industry has used deterministic intrinsic travel time to analyze the effect of delay propagation through the network (Kondo, 2008; AhmadBeygi & Cohn, 2010). In other words, the first waves of aircraft have stochastic travel times but subsequent waves are considered on-time, so any delay caused is due to the first wave propagating through the network. Arikan, Deshpande, and Sohoni show that this approach overestimates the total propagated delay. The authors utilize stochastic arrivals of all waves in their calculation of a schedule robustness measure that rates airlines based on their likelihood of meeting their scheduled departure times (Arikan, Deshpande &

Sohoni, 2013). This thesis follows the same wave logic, utilizing stochastic intrinsic and propagated delays to provide a better estimate on delay propagation effects.

Dunbar, Froyland and Wu discuss the growing difference between airlines profits and expected profits due to failure to incorporate appropriate uncertainty into the planning of airline schedules. The authors argue that current airline schedules are inflexible, performing poorly as delays propagate through the network (Dunbar, Froyland, & Wu, 2012). Typically, the airline scheduling problem is solved via Bender's decomposition with the objective of maximizing profit. Klabjan, Johnson, Nemhouser, Gelman, and Ramaswamy solve the airline problem by adding plane count constraints sequentially to allow a feasible routing to be attained (Klabjan, Johnson, Nemhouser, Gelman, & Ramaswamy, 2002). Dunbar et al. introduce a slack variable to the problem and change the objective to minimize total cost associated with propagated delay rather than maximizing profit. The slack between an arrival and subsequent departure is the difference between the scheduled arrival time and departure time, minus the mean turnaround time. By incorporating this algorithm with existing airline optimization models, the authors have shown a decrease of 8.91% in total delay compared to the methodology of Weide, Ryan, and Ehrgott (Dunbar et al., 2012; Weide, Ryan, & Ehrgott, 2009). We use the concept of propagated delay and mean turnaround time to create an optimized daily air plan. We then compare the optimized air plan to the empirical data to show the effects of propagated delay on the model.

Weide, Ryan, and Ehrgott detail the complexity of airline scheduling problem by splitting the scheduling problem into five separate planning problems: schedule generation, fleet assignment, aircraft routing, crew pairing, and crew rostering. Each scheduling problem is completed sequentially, with the output of one problem used as input to the next (Weide et al., 2009).

The first problem completed is schedule generation, which includes forecasting demand in each market, assessing available resources, and evaluating competitor behavior. Schedule generation also takes into account the cost of operations by market, expected fares, airport contracts, whether to schedule connecting or direct flights, etc. Schedule generation is typically produced six months in advance for North American airlines to facilitate the follow-on planning problems. Schedules are produced at the corporate level; for operational reasons and loyalty of frequent business customers, schedules rarely change significantly from week to week. Following the schedule generation, aircraft are assigned and then crews are assigned (Weide et al., 2009).

The DOD method of schedule generation is completely opposite from the airlines, schedules are built from the lowest unit level (squadron) concurrently with crew assignment and within the limitations imposed by aircraft availability. The squadrons provide a copy of their signed squadron schedule to station Air Operations the day before execution. Air Operations then combines all schedules into a cohesive daily air plan, with potentially up to 19 squadron schedules. The daily air plan is the critical document used to track operations at the airfield; it contains the total number of planned departures and arrivals, type of aircraft, flight composition (1–4 aircraft), time and duration of field carrier landing practice (FCLP) events, and so on. Air operations does not modify any squadron schedules for the sake of synchronizing the daily air plan. Therefore, the daily air plan is not optimized in any respect.

In Weide et al., the authors discuss improving scheduling by integrating schedule generation, aircraft routing and crew pairing into one large model. By allowing flights to deviate within a time window for departing flights, the authors were able to create a more efficient schedule. This, however, requires a central knowledge of the constraints, such as pilot qualifications and availability, which simply is not known above the squadron level. Due to the inherent differences in military and civilian airline scheduling, the approaches utilized in Weide et al. do not apply to our problem. In order to effect change in the decentralized nature of military scheduling, changes must be incorporated prior to the squadrons' writing their schedule. Two realistic methods present themselves; leadership can direct policy changes to the squadrons, or squadrons can use a scheduling tool that produces a more efficient schedule when aggregated across all squadrons on station. Realistically, a scheduling tool would have to be simpler, quicker, and easier to use than current SHARP (Sierra Hotel Aviation Readiness Program) and ISIS (Integrated Shipboard Information System) software in order to gain support.

Arikan, Deshpande, and Sohoni propose that post-flight fuel consumption is attributed to two factors; ground fuel burn rate and time duration (Arikan et al., 2013). Fuel burn rate is reduced through re-engineering or through acquiring new aircraft and is therefore considered fixed in this thesis. Time duration is typically recognized as the variability of the intrinsic travel time (which does not take into account conditional effects from the population of aircraft such as queuing), and the propagation of variability through the airfield network (the dependence of subsequent flights on current operations) (Arikan et al., 2013). We model both these factors in this thesis.

Variability in travel time is affected by randomness in conducting a series of independent flight-line operations. For example, the duration of time an F/A-18 spends conducting a crew-swap (where a new pilot boards the aircraft for the next flight) depends on the timeliness of strapping in, conducting checklist procedures, receiving flight authorization, addressing any maintenance issues, and so on. These factors can add up into several minutes of delay. Because most DOD airfields, including Oceana and Lemoore, have congested schedules, delays from one aircraft propagate to several, having a compounding effect on the airfield network.

B. FEDERAL AVIATION ADMINISTRATION PROGRAMS

The FAA revolutionized the National Airspace System paradigm through the advent of the Collaborative Decision Making (CDM) program. The CDM is a macro-level joint venture “aimed at improving air traffic flow management through increased information exchange among aviation community stakeholders” (Federal Aviation Administration, 2014a). CDM includes members from government, commercial airlines, private airlines, and academia collaborating for solutions to common problems. CDM agreements such as the Ground Delay Program (GDP) and Collaborative Routing (CR) have transformed Air Traffic Control Management (ATCM) from a traditional consolidated control to a more de-centralized management system (Federal Aviation Administration, 2014b). While the DOD does not possess the manpower to implement a full ATCM, we can improve efficiencies through some practical changes.

GDP can be leveraged by DOD installations in order to improve cost saving efficiency. The GDP reduces airport congestion by delaying takeoffs when the receiving airport is projecting traffic that will exceed capacity. GDP uses an Airport Arrival Rate (AAR), that when exceeded, causes the controlling air traffic facility to notify Air Traffic Control System Command Center (ATCSCC), which then triggers a GDP. The GDP remains in effect until the controlling facility reports an acceptable AAR (Federal Aviation Association, 2014b). In this thesis, we analyze the effect empirical AAR's have on ground fuel consumption from landing to engine shutdown. In particular, we study the effect peak arrival windows have on delays in the after-landing process and conduct sensitivity analysis by varying AAR's. In an effort not to affect proficiency, readiness and safety, this thesis is limited to finding fuel conservation opportunities in post-flight operations.

C. HEALTHCARE QUEUING MODELS

Queuing theory developed in the healthcare industry provides a very relevant and interesting comparison to our analysis. Healthcare organizations vary in scope and scale, as do airfields, but they consist of a standard set of related processes that a patient must undergo in order to complete a visit. Patients arrive, check in, wait for service, obtain service, and depart. Similarly, an aircraft cannot complete a mission until it processes through departure, arrival, post-flight procedures, and engine shutdown. In service industries such as healthcare, arrivals (e.g., emergency room visits) are typically stochastic. Even organizations that have scheduled arrivals, such as a dentist's office, still experience some intrinsic variation in arrival times (Creemers & Lambrecht, 2008; Green, Green, Giglio & Soares, 2006; Gupta, 2007). In these organizations, there is an inherent mismatch of demand and available resources and capacity leading to a queuing at bottleneck processes. In military scheduling, the scheduled arrival rate of aircraft, published in the daily air plan, is not known until the night prior to execution and resources for the following day are essentially fixed. Departure and arrival time of aircraft vary due to a large variety of factors including weather, maintenance, runway changes, ATC routing, etc. This leads to a similar variability in arrival rates (Green et al., 2008; Gupta, 2007).

Supply, duration, and capacity of resources in the healthcare industry also tend to be stochastic in nature. Doctors' time to complete a routine checkup may vary depending on the type and number of complications the patient is reporting, the length of his or her medical record, patients' ages, the requirement to fill out prescriptions, etc. These are the direct variability effects. With a limited number of doctors available, delays from one patient's examination may propagate to the next patient's and so on, creating carryover effects. This inherent variation in both arrivals and processes lends itself to being analyzed by queuing theory. As such, a considerable amount of research has shown how queuing theory can be utilized to reduce queue and delay effects on patient flow in a variety of healthcare organizations. This thesis uses the same queuing methodology utilized in the healthcare industry by incorporating basic G/G/s processes into a network to model airfield operations.

D. DEPARTMENT OF DEFENSE AVIATION ENERGY CONSERVATION

Efforts in academic literature that focus on military aviation energy conservation are scarce. The majority of literature is directed towards reducing energy consumption through future procurement programs with little quantitative recommendations using existing equipment. One notable exception is the Capstone project More Flight-Less Fuel by Gerber and Clark (Gerber & Clark, 2013). In More Flight-Less Fuel, the authors analyze ground operations at NAS Lemoore through empirical data entered into a Simio model to determine (i) where airfield resource capacity constraints are and (ii) how fluctuations in arrival rate affect airfield efficiency. The authors report that a main factor in ground fuel consumption is the over-use of refueling at the hot skids stations (Gerber & Clark, 2013). Hot skids are refueling stations where the aircraft is not required to shut off engines. The motivation for our thesis is to create a follow-on decision support tool that can be utilized by all fighter bases to analyze ground operations.

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III. METHODOLOGY

In Chapter III, we introduce our simulation software, and discuss our objective and scope. We lay out the model from end to end and briefly discuss the logic of each process an aircraft goes through. We introduce our Microsoft Excel graphic user interface used to import data into the model. We conclude by describing our methodology for optimizing aircraft among training squadrons at Oceana and Lemoore.

A. INTRODUCTION

Naval aircraft burn over 600 million gallons of fuel each year. Over the foreseeable future, the defense budget will continue to decline. By 2017, the defense budget is expected to reduce by 20% (Department of Defense, 2013). Sequestration would further reduce the defense budget by $50 billion each year through 2021 (Watters, 2013). Each gallon of gas must be conserved in order to meet mission requirements in a constrained resource environment. To address this challenge, the Chief of Naval Operations (CNO) established Task Force Energy with the goal of “increasing energy awareness and conservation, raising the visibility of energy in budgeting and acquisition, and identifying the right initiatives to promote energy efficiency and alternative energy use afloat and ashore.” Task Force Energy coordinated a team of aviators, engineers and analysts to stand up the Aviation Energy Conservation Program (Air ENCON). Air ENCON is the lead program responsible for implementing energy-conservation best practices across the naval aviation community (Air ENCON, 2014). While several energy conservation practices have been adopted by carrier air wings and squadrons, there are few that span across the fleet. Our goal in this thesis is to find squadron-level efficiencies and bridge the gap between tactical and institution-wide recommendations. By taking improvements found at a tactical level and examining them with a “Big Navy” lens we are able to determine if institutional-level best practices can be implanted, in turn improving not just one or two squadrons but the entire Naval Aviation Enterprise (NAE).To that end, we have created a model that simulates daily flight operations at the Navy's two largest airbases, Naval Air Station (NAS) Oceana and NAS Lemoore using data collected by Commander Strike Fighter Wing Pacific (CSFWP) and staff, Commanding Officer Strike Fighter Wing Atlantic (CSFWA) and staff, training squadrons VFA-106 and VFA122, and both bases' Fuels Division Managers, Air Traffic Control Officer/Chief, and Supply Officers. In order not to detract from readiness, proficiency or safe flight operations, we have focused our effort at simulating post-flight operations.

B. SIMULATION

One of the most important decisions we had to make early in the process was in determining an appropriate simulation software package to run our models. In order to model airfield operations at Oceana and Lemoore we required simulation software that had the following key attributes:

- Allow concurrently running interactions and processes with a large number of entities and objects
- Define and change attributes for entities, objects, and global variables
- Use entity variables, global variables, and mathematical expressions in the decision logic
- Import and export data from other applications (e.g. an Excel spreadsheet)
- Offer concurrent animation that displays key elements of the system dynamically travelling through the system in real time, to help assist in debugging and model validation

1. Simio

We chose to implement our model in the Simio (Simulation Modeling framework based on Intelligent Objects) software suite (Kelton, Smith & Sturrock, 2013). Simio is a graphical object-oriented modelling framework that allows users to develop their own intelligent objects and build a model around them from the ground up. Simio also supports seamless routing of objects through processes and events, using both continuous and discrete distributions. Figure 1. depicts the Simio interface in facility view of the Lemoore model. The user navigates through the use of ribbons similar to those in Microsoft Office 2007.

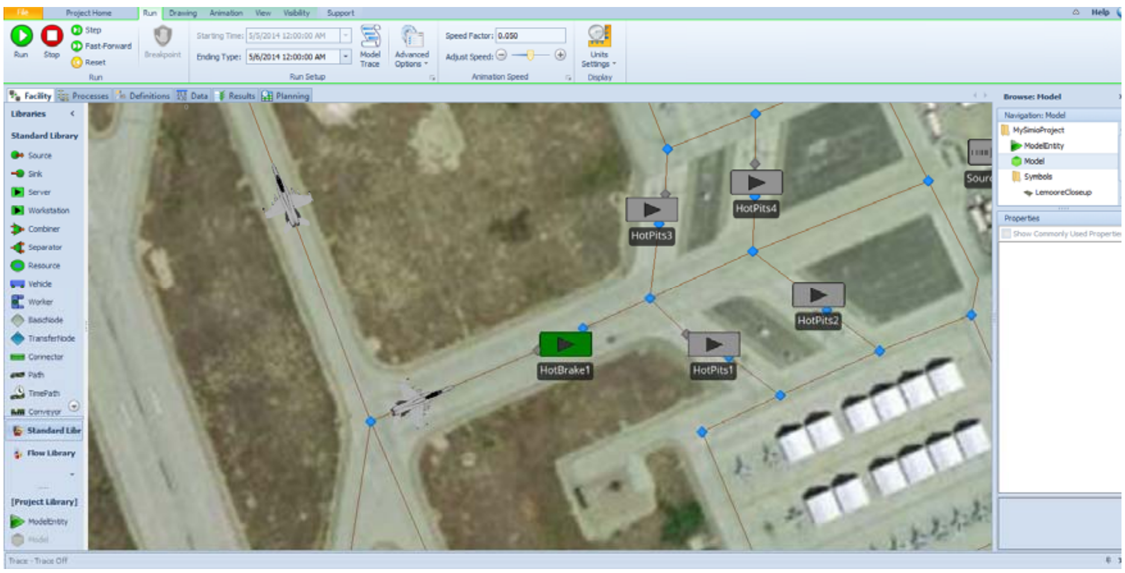

Figure 1. Screen capture of Lemoore Simio model.

Simio is built around object-oriented logic. An *object* can be a service station (e.g., patient check-in at a Hospital) or a movable entity (e.g., the patient or doctor). Objects are dynamically routed in and out of other objects through the use of connector *paths* or *networks*. A set of *objects* and their interrelations create a model. *Source* and *sink* objects are two special purpose-objects used to create (*source*) or destroy objects (*sink*). The true advantage of Simio is that objects can be completely designed by the user. Objects are defined by *properties, states,* and *processes*.

- *Properties* are static input parameters that do not change during the running of a simulation.
- *States* are dynamic values assigned to objects that may change as the model executes.

- *Processes* define the behavior of a user-defined object. A process is comprised of *steps* and *states*. *Steps* are combined into process flows which in turn alter an objects *state*. *Processes* can be added to object's logic and executed at specific points though the simulation run (e.g., upon failure of a server object).

- The object's *logic* is defined by the set of properties and states assigned to the object and any add on *processes* the user includes. This might include process logic that assigns a particular routing to an aircraft depending on whether the aircraft has another departure scheduled or not. As shown in Section I, our model uses *properties, states,* and *processes* extensively.

2. Simio Resources

Simio resources come in three forms:

- The support tab in Simio, shown in Figure 2, provides quality information. In particular, the Simbits provide sample models with detailed explanations.

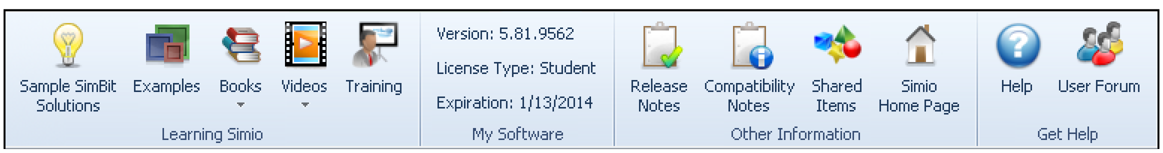

Figure 2. Simio support tab.

- A website containing general information and user forum is available at www.simio.com/forums (login required).

- Academic textbooks such as Simio & Simulation Modeling and Simio Reference Guide are available online (Kelton, 2013: Simio Reference Guide, 2006).

C. OBJECTIVE

Our objective is to simulate daily flight operations at Oceana and Lemoore, identify bottlenecks in the system, and experiment with potential process changes and scheduling improvements. Our approach focuses on model flexibility through the use of a user-friendly Microsoft Excel interface. Our model covers all significant aircraft procedures from engine start to shutdown, including taxi, marshal, takeoff, land, hot brake checks, ordnance de-arm, hot skid operations, post-flight checks, engine shutdown, and fuel truck refueling. Parameters for all post-flight procedures, aircraft, fuel truck, and schedule are all done through our GUI. Our objective metric is the average time with engines online from the moment when wheels touch down to engine shutdown. Average TEO is calculated by summing all $TEO_{x,w}$, where $TEO_{x,w}$ is the time with engines online for aircraft *x* on wave *w*, and dividing by the total number of flights, $Landings$.

Sets:

$x \in X = \{1, 2, 3, \ldots 100\}$	Aircraft number unique to each aircraft
$w \in W = \{1, 2, 3, 4\}$	Wave number; each launch and recovery of aircraft *x* is a wave for that aircraft

Objective metric:

$$\frac{\sum_{X,W} TEO_{x,w}}{\sum_{X,W} Landings_{x,w}}$$

We calculate cost as a function of the amount of time spent with engines online after the flight multiplied by the fuel burn rate of that aircraft and the cost of maintenance. An F/A-18CD burns JP-5 (standard jet propellant gas used by naval aircraft) at a rate of 2.941 gallons per minute (gpm) (CNO, 2012a; CNO, 2012b). F/A-18EF burn JP-5 at a rate 3.676 gpm (CNO, 2012a; CNO, 2012b). Current fuel price is $3.64/gallon (Defense Logistics Agency, 2013). Therefore, the cost of an idling aircraft is $10.71/minute (F/A-18CD) and $13.38/minute (F/A-18EF).

D. SCOPE

One model run simulates a 16-hour weekday schedule from 0800–2400. We use a one-hour warm up period (0800–0900). Lemoore’s operating hours are 0800–2400 so our simulation always captures the initial takeoff and final landing. Oceana operates 24 hours a day. However, based on historical data, aircraft rarely take off prior to 0800. In fact, over the four weeks of data collected, only one flight departed prior to 0800. Figure 3. shows the average number of daily landings at Oceana from 1 May to 31 May, 2014 and Lemoore from 1 March to 31 March, 2014. Note that both airfields peak arrival period is between 13:00 and 14:00 local time. Also note that the rate of arrival is steepest between approximately 9:30 and 10:45.

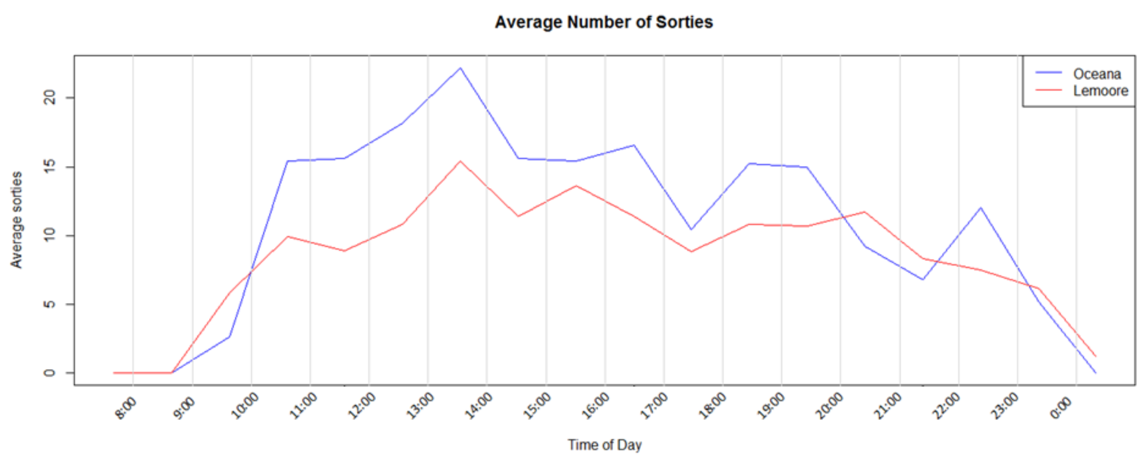

Figure 3. Average daily landing times at Oceana (1 May–31 May, 2014) and Lemoore (1 March–31 March, 2014).

E. ASSUMPTIONS AND LIMITATIONS

Our model does not incorporate weather effects, or airfield emergencies, which can alter the execution of the air plan by limiting the available land times, this could create additional peaks in landing and increasing delay queues. Our model also does not simulate transient aircraft which may affect fuel truck availability for airfields with heavy transient traffic. In the simulation, fuel trucks operate with 100% reliability and all processes are assumed to be reliable. However, process time is stochastic. The capacity of hot skids is considered infinite with 100% reliability in our model.

F. DATA COLLECTION

All data in this model was collected from the staffs of Commander Strike Fighter Wing U.S. Pacific Fleet (CSFWP), Commander Strike Fighter Wing U.S. Atlantic Fleet (CSFWA), NAS Lemoore Air Traffic Control, NAS Oceana Air Traffic Control, Fleet Logistics Center San Diego Site Lemoore, and Fleet Logistics Center Norfolk Site Oceana. Where data was not readily available, subject matter experts and personal experience were utilized. The data is used to structure the model parameters and establish process logic of events. Information on data collection sources and techniques is dispersed throughout this chapter when the data's usage is described.

G. OVERALL LOGIC

While Oceana, Lemoore, and all Navy fighter airbases differ in location and composition of critical infrastructure, they generally share a set of common elements; specifically, multiple squadrons, multiple runways, a complex taxi structure, multiple hangars, marshal areas, hot pits, and fuel trucks. In addition, aircraft generally follow the same set of routing procedures at each airfield. Figure 4. describes the process logic that each aircraft is routed through in the simulation. We have developed base models for NAS Lemoore and NAS Oceana but any air installation could by created by a user with a basic Simio background.

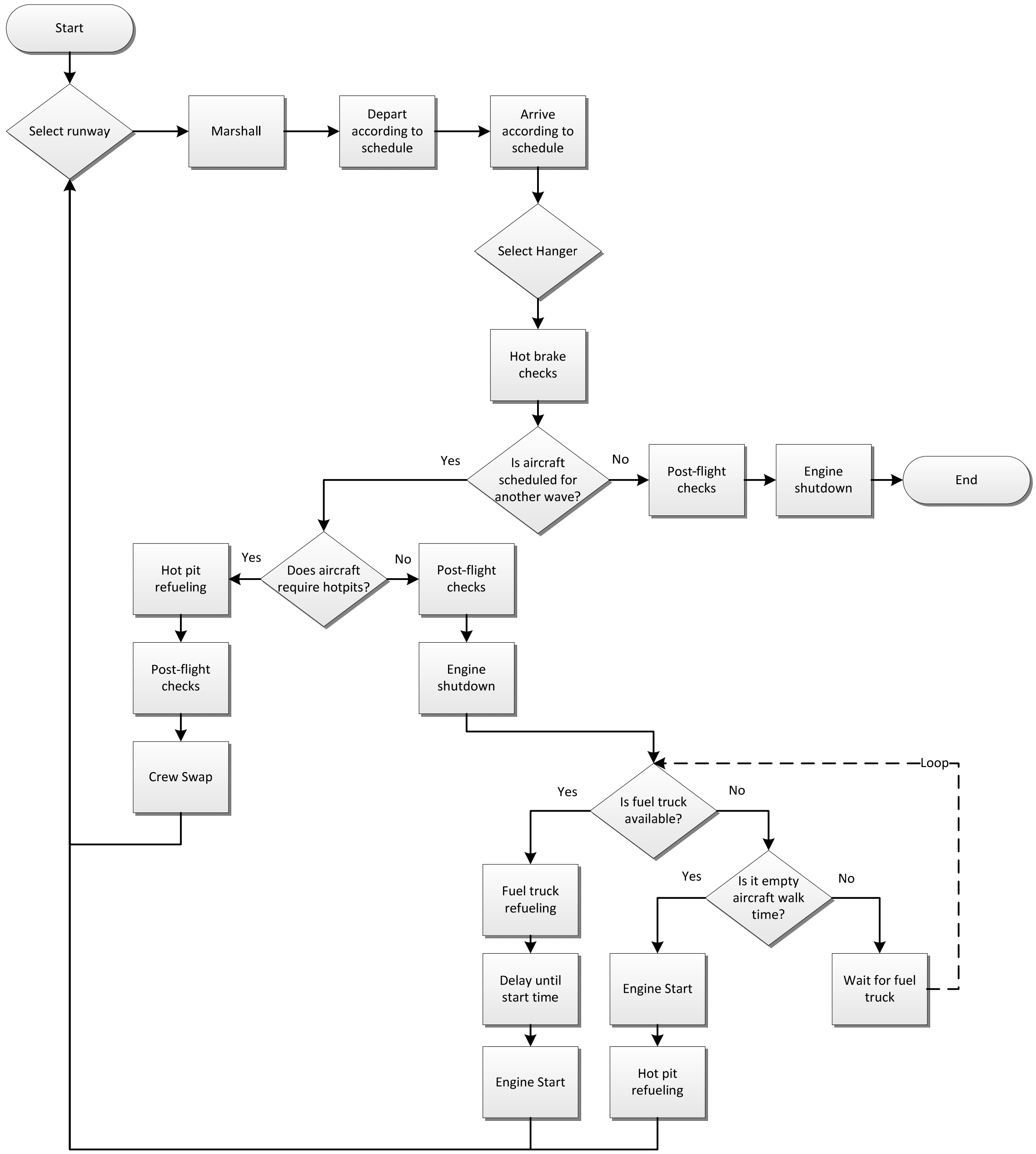

Figure 4. Flowchart of overall model logic.

H. ROUTING LOGIC

Routing logic for each airfield is created by accurately representing the airfield architecture and routing aircraft through the appropriate taxiways and processes according to squadron and aircraft type. First, we create the airfield infrastructure specific to the base being modelled, including the taxi-way network, runways, hot pit areas, fuel trucks, and so on. Actual distance of taxi-ways is incorporated in the length property of each path in the network through the use of Google Earth ruler. Figure 5. shows the distance calculation for a VFA-122 aircraft landing on runway 32L at Lemoore. The aircraft departs the runway on taxiway Bravo and proceeds to the hot brake check area, traveling a distance of 1,414 feet. Aircraft travel at standard taxi speed of 10 miles per hour (mph). Fuel truck routing follows a similar network, with the addition of paths to and from the fuel depot and truck refueling stations. Fuel trucks travel at 10 mph on taxiways and 5 mph in squadron line areas.

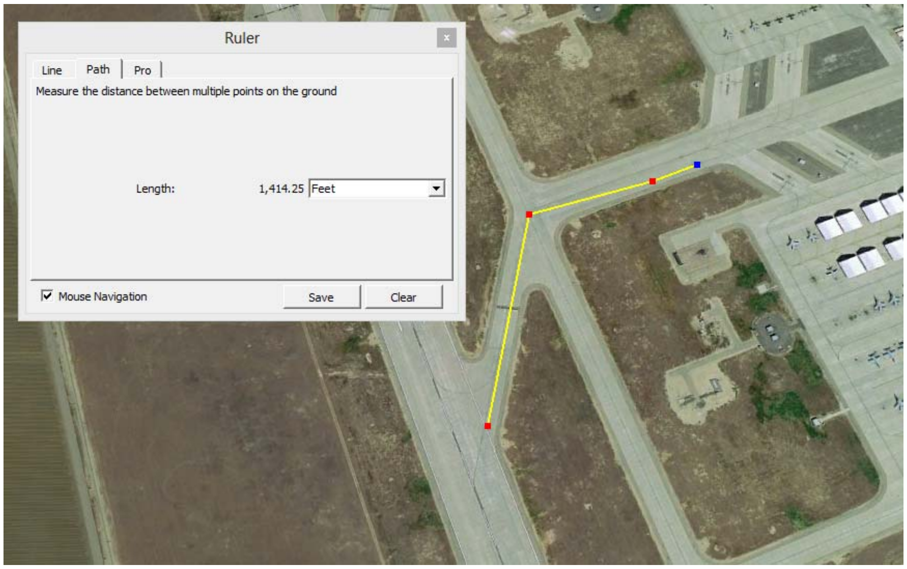

Figure 5. Sample distance calculation using Google Earth ruler (from Google, 2010).

We assign properties to each aircraft that are queried to determine the aircraft’s specific routing at decision points in the model. Each aircraft is assigned a hangar number specific to its squadron and a line number specific to its aircraft number (unique for each aircraft). Routing through taxiways and through specific squadron-assigned process areas is determined based on the aircraft’s squadron. For communal areas such as where the hot brake checks and the hot skids are located, an aircraft’s squadron number determines the appropriate hot brake check and hot skids to route that aircraft to. For instance, of the ten hot skids at Lemoore, VFA-122 is allocated two of them (hot skids 1 and hot skids 2), as such, VFA-122 aircraft will only be routed through hot skid 1 or 2.

Airfield diagrams showing the runway and taxiway structure for both airfields are shown in Figure 6. The arrival runway is based on historical data collected from tower traffic count reports. On Lemoore, 82% of arrivals occur on runway 32L and 18% runway 32R (N. Black, personal communication, 19 February 2014). On Oceana, 45% of arrivals occur on runway 23, 42% on runway 5, 11% or runway 32, and 1% on runway 14 (J. Morris, personal communication, 10 May 2014). Our model assumes all aircraft land on the inboard runway (runways 11R, 32L, 23L and 5R).

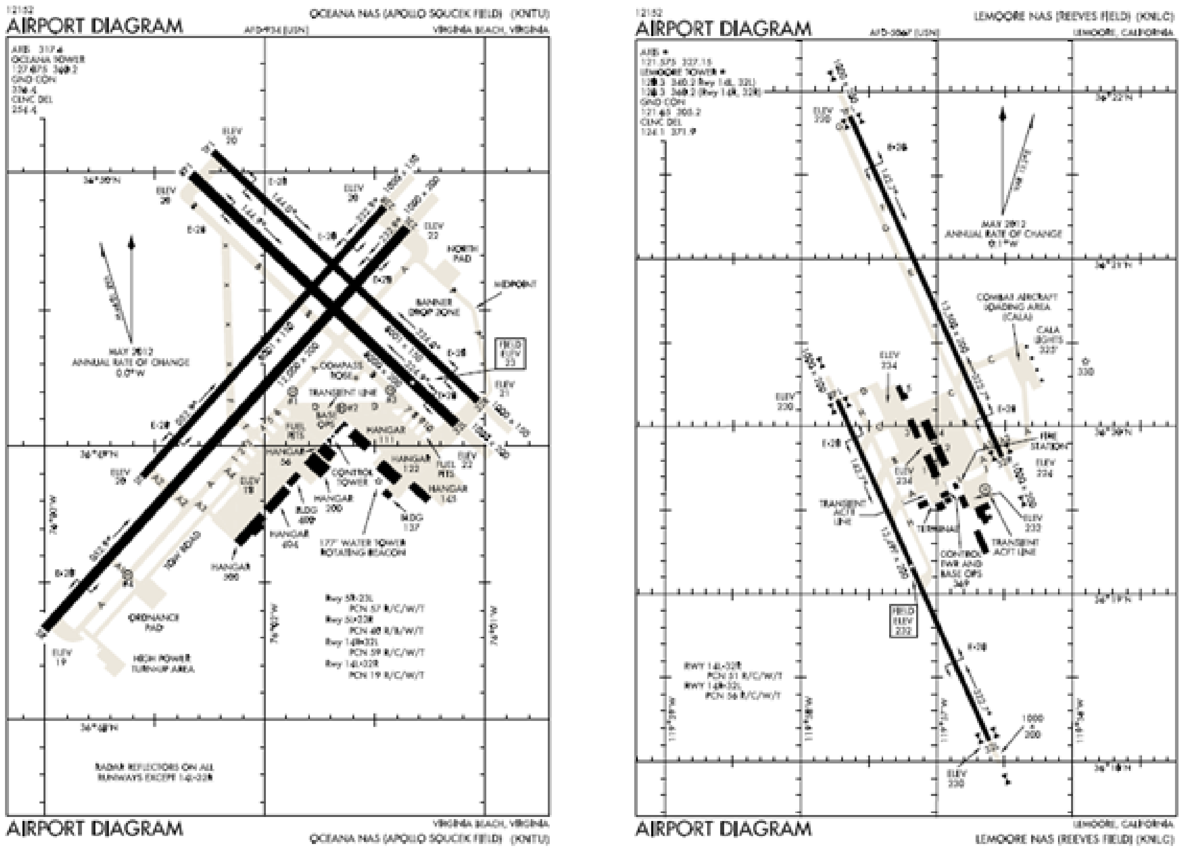

Figure 6. Airfield diagrams of Naval Air Station Oceana (left) and Naval Air Station Lemoore (right) (from Department of Defense, 2012).

A graphic representation of the hangars and line areas of Oceana and Lemoore is shown in Figure 7. Each hangar is home to anywhere from 1–4 squadrons. We split each hangar into line areas 1 and 2 to decipher between east and west side of hangar (or north and south, etc.). Squadron aircraft are routed to the appropriate line based on their squadron's location in the hangar. The line area is where post-flight checks, crew swap, engine shutdown, and engine start processes occur.

Figure 7. Hanger and line areas of Naval Air Station Oceana and Naval Air Station Lemoore.

I. PARAMETERS

As mentioned in Section B, Simio objects are highly parameterized. We split our objects into two types: *entity objects* and *server objects*. *Entity objects* are moveable objects that travel through servers in the model. The two types of entity objects we use are aircraft and fuel trucks. *Servers* (also called workstation) are stationary objects that execute a process when an aircraft or fuel truck arrives. All the processes that an aircraft enters are server objects (e.g., flight, hot brake check, hot skids, post-flight checks). Connections between a set of servers create the model architecture. *Parameters* are assigned to either a model entity (private) or to a model itself (public). Public parameters can be called upon by any process at any time. Private parameters are specific to the entity being queried and require the unique entity to pass through the process. A complete list of parameters split by aircraft, fuel truck, and model are shown in Tables 1 through 4.

Indices and Sets	
Label	**Definition**
$sq \in SQ = \{1,2,3...30\}$	Squadron number
$x \in X = \{1,2,3,...100\}$	Aircraft number
$w \in W = \{1,2,3,4\}$	Wave number

Table 1. Indices and sets used in the model.

Aircraft States			
Label	**Definition**	**Type**	**Dimension**
AC_x	Aircraft Type: Used for processes that require aircraft type as an input (e.g. processing time at hot skids)	Integer	Scalar
AD_x	Arrival deviation of actual arrival time around scheduled arrival time	Real	Scalar
$AS_{x,w}$	Scheduled arrival time for aircraft x in wave w	DTS	Vector
$AA_{x,w}$	Actual arrival time for aircraft x in wave w	DTS	Vector
FT_x	Scheduled flight time of aircraft x, used in flight process $(AS_{x,w} - DS_{x,w})$	Real	Scalar
$Lead_x$	Current lead/wingman assignment for aircraft x (1 =Lead, 2 = Wingman)	Integer	Scalar
$Priority_x$	Priority assignment of aircraft x, each aircraft assigned to the same event/flight have the same priority	Integer	Scalar
$RowAssignment_x$	Current row assigned to aircraft x, the row number on the air plan that this aircraft will populate its state assignments from	Integer	Scalar
$TEO_{x,w}$	Time with engines online post flight	Real	Vector
TI_x	Taxi instructions for aircraft x, based on hanger and line assignment and hot skid or truck refueling	Integer	Scalar
$Wave_x$	Current wave number assigned to aircraft x	Integer	Scalar

Table 2. Variable definition of aircraft states.

Aircraft Properties			
Label	**Definition**	**Type**	**Dimension**
SQ_x	Squadron number of aircraft *x*	Integer	Scalar

Table 3. Variable definition of aircraft properties.

Model States			
Label	**Definition**	**Type**	**Dimension**
$Landings_{x,w}$	Number of landings	Integer	Vector
$MinTurnTime_{sq}$	Minimum turnaround time for each squadron sq. If turnaround time is less than this number the aircraft must refuel at the hot skids, else it may refuel via fuel trucks	Integer	Vector
ORD	Does aircraft have ordnance? (yes=1, no = 0)	Binary	Scalar
$RNwave1_{sq}$	Row number corresponding to the next departure scheduled for each squadron sq in wave 1	Integer	Vector
$RNwave2_{sq}$	Row number corresponding to the next departure scheduled for each squadron sq in wave 2	Integer	Vector
$RNwave3_{sq}$	Row number corresponding to the next departure scheduled for each squadron sq in wave 3	Integer	Vector
$RNwave4_{sq}$	Row number corresponding to the next departure scheduled for each squadron sq in wave 4	Integer	Vector
$TimeNow$	Current model time	DTS	Scalar

Table 4. Model state assignments.

J. PROCESS LOGIC

As entities (or aircraft) route through the model, the aircraft's behavior at each object is determined by the process logic of the associated object. Aircraft are initially created through model initiation and routed through a subset of the processes listed in this section. The specific route is determined by the aircraft's hanger and line assignment and the overall routing logic shown in Figure 4.

1. Model Initiation

Upon selecting “run,” the model initiates at 0800 and begins creating aircraft according to the daily air plan. The model (source) creates aircraft only up to the number of ready for tasking (rft) aircraft available for each squadron. For instance, if VFA-122 has 10 rft aircraft, the model creates 10 aircraft to fill the first 10 sorties; this is considered the first wave. All subsequent sorties will be filled by those 10 aircraft once they return from the first wave, creating the second wave, third wave, etc., up to the maximum number of waves allowed by the squadron. Aircraft are initialized with all the parameters required to route the aircraft appropriately; $AC_x, \mathrm{Priority}_x, \mathrm{Wave}_x, BS_x,$ and Lead_x. Once an aircraft is created it taxis to the marshal area.

2. Marshal

The first process entered is the marshal area. The marshal area is where a flight of aircraft joins prior to takeoff in order to finish pre-flight checks and verify communication. Flights generally consist of one to four aircraft, referred to as a single (flight of one), section (two), light division (three), and division (four). Each flight is assigned a lead aircraft, flight lead, who has overall responsibility for the conduct of his or her flight. We assign flight lead with $Lead_x = 1$. For simulation purposes, there is no need to differentiate among wingmen. We assign each wingman $Lead_x = 2$. The batch size of the overall flight is tracked by BS_x and assigned to each member of the flight ($BS_x = 1$ for a single aircraft, $BS_x = 2$ for a section, $BS_x = 3$ for a light division, and $BS_x = 4$ for a division). Empirical data from daily air plans is used to determine batch size. When aircraft reach the marshal area they delay until their scheduled departure time. If all members of the flight are not at marshal by departure time, the entire flight delays up to 10 minutes. At 10 minutes past departure time, the flight will launch regardless of whether it is missing members or not.

3. Flight

The duration of each flight is determined by the scheduled flight time plus a stochastic estimate of the actual arrival time about the scheduled. Scheduled flight time is simply the arrival time minus the departure time, $AS_x - DS_x$, pulled from the air plan. The arrival deviation, AD_x, is an estimate of the difference between actual arrival times and scheduled arrival times collected from aircraft landing at Lemoore in August 2012 (Gerber, 2013). We fit arrival deviations using a normal distribution with $\mu = 3.99$ and $\sigma = 13.21$, making the flight duration $(AS_x - DS_x) + normal(3.99, 13.21)$, shown in Figure 8.

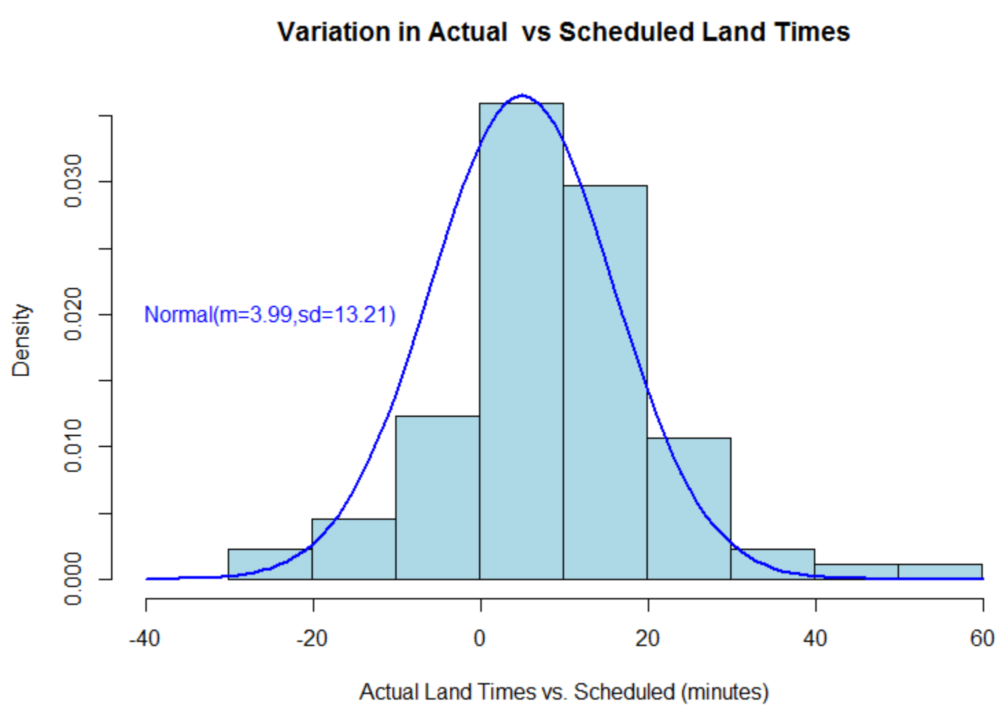

Figure 8. Actual variation in landing times compared to scheduled times collected from Lemoore (after Gerber & Clark, 2013)

4. After Landing

Immediately after landing, each flight separates into individual aircraft. Following the first wave of landings, aircraft proceed through *WaveTwo* process logic, shown in Figure 9. The *WaveTwo* process determines whether there is another departure line on the air plan to assign each aircraft to. If there is, the aircraft states are updated with the new departure information and the aircraft is routed to the appropriate processes discussed later in this section (e.g., proceed to hot skids or the line). If there is not another departure, the aircraft is routed back to the line for engine shutdown and fuel truck refueling. Upon landing on waves two and three, each aircraft proceed through *WaveThree* or *WaveFour* process logic respectively. These processes are essentially the same as *WaveTwo* but with assignments based on the current wave.

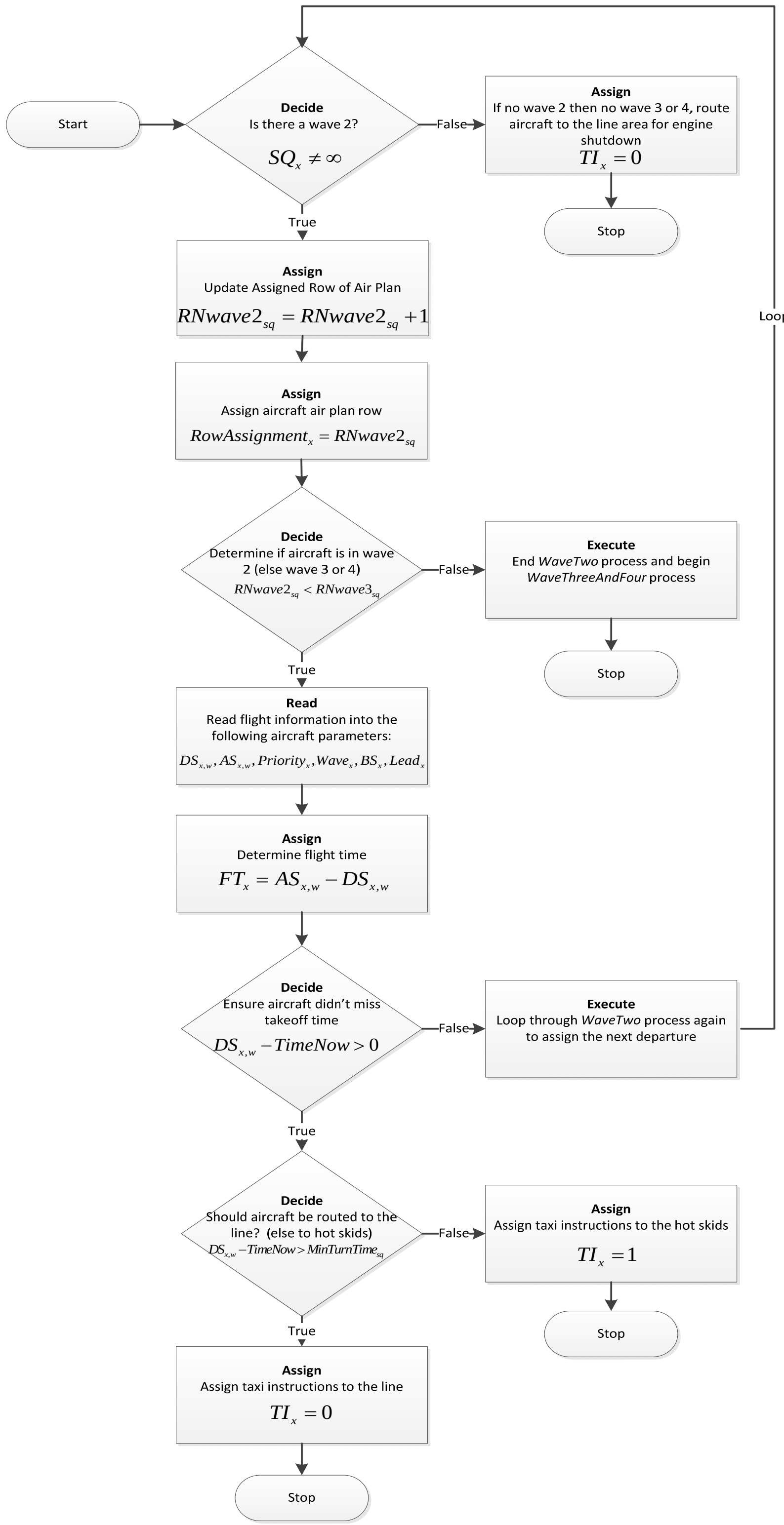

Figure 9. Flow chart of *WaveTwo* process. Following the first wave, aircraft proceed through this logic to assign next departure information.

5. Hot Brake Checks

Hot brake checks are the first post-flight landing procedure that aircraft enter. All F/A-18 aircraft are required to have brakes checked after landing. Upon entering the hot brakes, a maintainer checks the temperature of the brakes to ensure they are not overheating due to the friction applied when landing. In addition to checking the brakes, ordnance must be de-armed in this area (if the aircraft is carrying ordnance).

Most squadrons complete additional procedures at the hot brake check area. The two most common procedures are degaussing the aircraft and safing the captive air training missile (CATM-9) (C. Gerber, personal communication, 18 February 2014; M. Sand, personal communication, 8 April 2014). The aircraft is degaussed from static electricity by swiping a grounded wand across the canopy. CATM-9's are safed by pulling a lever into the safe position and placing a cover over the seeker head of the missile. Since the majority of squadrons conduct these procedures in the hot brake check area, we incorporate them in the process time at hot brake checks for our default settings. We use a triangular distribution with a minimum of one minute, maximum of three and a mode of two (triangular(1,2,3)) to represent the hot brake check processing time for an aircraft without ordnance.

If an aircraft is carrying ordnance, we add additional process time to conduct the de-arm procedure. Ordnance time is triangular (.5,1,1.5) and is activated by coupling process time to a binary ORD model state, which contains the value one if the aircraft is carrying ordnance and zero if it is not. It is estimated that approximately 65% of aircraft require ordnance based on mission sets flown (NAVAIR, 2012). Therefore, our base models assign ORD the value of one on 65% of occurrences.

6. Hot Skids

Hot skids (also called hot pits) are fixed refueling locations with their own in-ground fuel tank. Each hot skid typically has two fuel hoses requiring a crew of three to four personnel to operate. Each hot skid also has a dead-switch operator who controls the safety switch to shut off fuel flow in the case of an emergency. Hot skids refuel at a rate of 120 gpm for an F/A-18's external fuel tanks and 200 gpm for internal tanks.

The fuel trucks also use the hot skids to refuel. Fuel trucks refuel at a rate of 500 gpm (M. Fahner, personal communication, 19 February, 2014). The capacity of hot skids is considered infinite with 100% reliability in our model. Hot skid process time is determined by the aircraft's initial capacity (AC_x) minus how much fuel was burnt in flight (FT_x).

There are 10 hot skids at Oceana. Hot Skids 1–6 parallel runway 5 and 23; hot skids 7–10 parallel runway 14/32. Hot skid six is used purely to refuel fuel trucks. Hot skid nine is configured for large aircraft and, as such, only has one long hose attached. The remaining eight hot skids have two hoses each. The hot skids are communal and require squadron maintainers to operate the hose and the "dead" switch. At Oceana, hot skids 1–6 and hot skids 7–10 are each assigned one fuels division recorder to keep receipts of all fuel evolutions on their assigned hot skids. The fuels division has approximately 110 personnel, all Navy except five civilians, and the division is run 24 hours a day, seven days a week in three shifts (H. Adair, personal communication, 8 April, 2014).

Lemoore also has 10 hot skids, two located at each hangar. Each hot skid has two refuel hoses. While hot skids are communal, squadrons only use the hot skids attached to their hangar. Squadron maintainers operate the hoses in 3–4 man crews but a fuel truck driver is required to operate the "dead" switch. Therefore, our Lemoore model requires a fuel truck to be at the hot skid while the aircraft refuels. Lemoore's fuel division comprises civilians employed from Fleet

Logistics Center San Diego. There are currently 22 fuel truck drivers, operating in five shifts per week.

7. Post Flight Checks

Post-flight checks occur after every flight in the squadrons' line area. Post-flight checks either occur after hot skids refueling or after hot brake checks, if the aircraft is proceeding to truck refuel. They include a standard set of checklist items requiring a fairly predictable amount of time to complete. Process time in post flight checks is triangular (2,3,4) in our base model and require no additional assets.

8. Engine Shutdown

Engine shutdown occurs after post-flight checks in the squadron's line area. We include the possibility of conducting maintenance troubleshooting in the engine shutdown process, which extends the processing time to seven minutes on rare occasions. Therefore, engine shutdown processing time is triangular (2,3,7) in our base model.

9. Fuel Truck Refueling

Following engine shutdown, an aircraft refuels via the fuel trucks if it had not already refueled at the hot skids. Fuel truck refueling requires a fuel truck with enough gas in the tank to refuel the aircraft. We assume fuel trucks are 100% reliable. Processing time is a function of the aircrafts initial capacity (AC_x) minus how much fuel was burnt in flight (FT_x).

Oceana has 15 fuel trucks, each with a 5,000 gallon tank. Fuel trucks are stationed at a central dispatch location at the departure end of runway 5R. Squadron maintenance radios fuels dispatch to request a refuel. At that time, a fuel truck is routed to the squadron line on a first-come first-serve basis. At Oceana, fuel trucks always refuel at hot skid six prior to returning to the dispatch, so any time a fuel truck is started at dispatch that truck is full. If a truck has finished refueling and still has enough gas, that truck will be rerouted to fulfill a new request if one is called in. If a truck is finished refueling and no more requests come in, that truck will return to dispatch (H. Adair, personal communication, 8 April, 2014).

Lemoore has 10 fuel trucks with 10,000 gallon tanks and one truck with an 8,000 gallon tank. The trucks are located at a central dispatch near the airfield tower. When a request for fuel comes in, a fuel truck is dispatched on a first-come first-serve basis. Following a refuel event, a truck will route to any unfilled fuel requests prior to returning to dispatch. Since a fuel truck is required for hot skid refueling as well at Lemoore, a fuel truck will fulfill whichever request occurs first. Trucks refill their own tank when there is less than 2,000 gallons remaining. Any idle truck returns to the central dispatch area (M. Fahner, personal communication, 19 February, 2014).

10. Crew Swap

Crew swap occurs after post-flight checks on aircraft that refuel at hot skids. During a crew swap, the aircraft is emergency braked and choked then the pilot shuts off the left engine and exits the aircraft, and a new pilot boards. We include final checks as part of the crew swap process. Final checks are the final systems and airframe checks conducted on the aircraft before the pilot and plane captain confirm it is safe to fly. The crew swap (including final checks) process time is triangular (15,20,30) in our base model (C. Gerber, personal communication, 18 February 2014).

11. Engine Start

The engine start process occurs for aircraft that have shut down their engines, if the aircraft is scheduled on a subsequent wave. The start time process includes starting the engines, conducting checklist items, and conducting final checks. 30 minutes is the desired engine start time for the majority of squadrons. However, events such as briefing long, walking late, and investigating maintenance gripes often delay the actual start time of the aircraft. We use a triangular (20,25,30) distribution for start time in our base model (B. Fiala, personal communication, 8 May 2014).

K. DATA ENTRY

All the process distributions and modeling logic mentioned in the preceding sections are imported into our model through our Excel interface. The user can adjust a wide variety of parameters including the number of aircraft, rft rate, number of squadrons, squadron hangar and line assignments, probability of carrying ordnance, process time distributions, number of fuel trucks, etc. A complete list of modifiable parameters is shown in Figure 10. The ability to manually adjust these parameters adds tremendous amount of flexibility to the model. Not only can the user experiment with changing parameters at a specific base without getting under the hood in the simulation software, the user can compare bases as well.

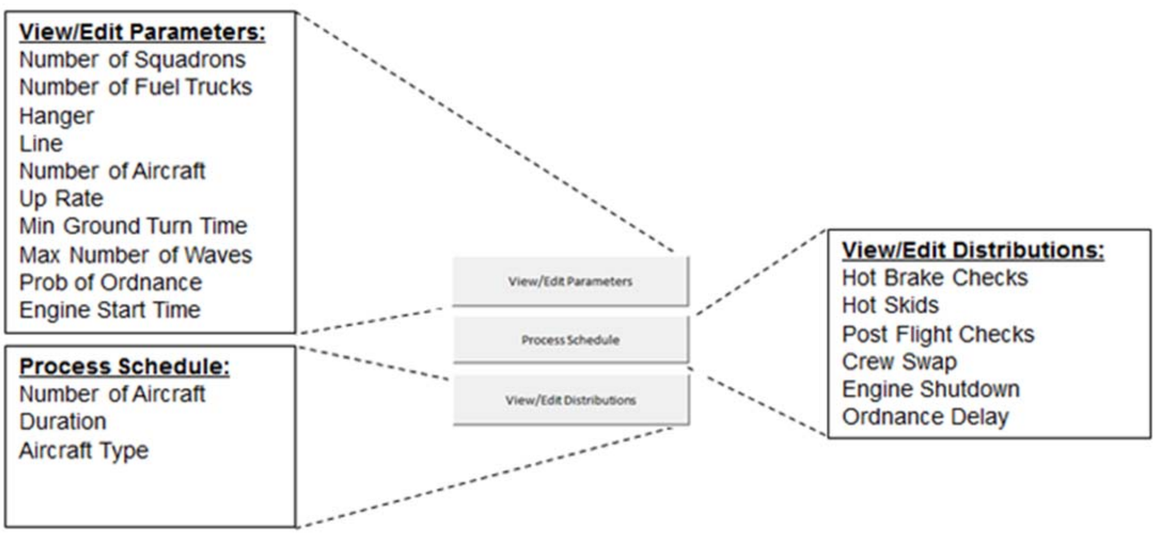

Figure 10. Parameters, process logic, and air plans are manipulated in Excel through four buttons and then imported into the model.

1. View/Edit Parameters

Parameters are edited through the use of two message boxes (part 1 and part 2), both of which are initially populated with the default values shown. Upon selecting view/edit parameters, the part 1 message box will pop up asking for the number of squadrons and number of fuel trucks, as shown in Figure 11. After the user enters the data by pressing enter part 1, the second message box appears, as shown in Figure 12. A generic data set is shown. Each field can be adjusted independently or the user can populate the entire message box with the last previously saved data by checking the box in the circled area. A description of each parameter is listed in Table 5.

Figure 11. User interface to input number of squadrons and fuel trucks.

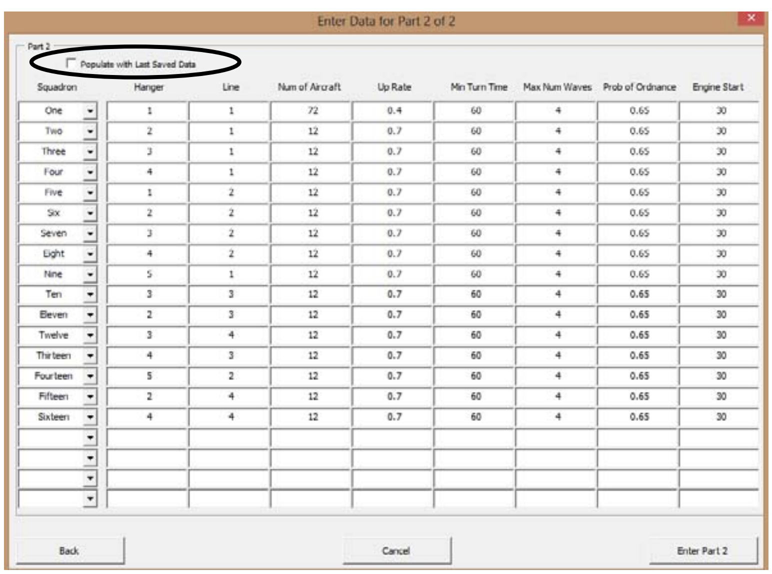

Figure 12. User interface to input parameters for each squadron.

Description of Parameters		
Parameter	**Type**	**Description**
Squadron	Text	Each squadron is assigned a number from one to twenty to represent its squadron number.
Hangar	Integer	Hangar assignment. Hangars are numbered 1-5 at Lemoore and 1-6 at Oceana.
Line	Integer	Line assignment in hangar line. Each hangar has two line assignments, 1 and 2, representing each side of the hangar.
Num of Aircraft	Integer	Number of aircraft assigned to each squadron.
Up Rate	Real	Up rate multiplied by Num of Aircraft provides the number of aircraft available to fly, or ready for tasking (rft) aircraft.
Min Turn Time	Integer (minutes)	Minimum time required for an aircraft to land, conduct fuel truck refueling and take off on the next wave. Any turn time less than Min Turn Time requires the aircraft to refuel via the hot skids.
Max Number of Waves	Integer	Maximum number of waves an aircraft can be scheduled for in a day. Typically four waves is the upper bound.
Probability of Ordnance	Real	Probability of an aircraft to be conducting a mission that requires inert ordnance.
Engine Start	Integer (minutes)	Engine start time prior to takeoff, standard to each squadron and used as the upper bound to actual stochastic engine start process time.

Table 5. Description of parameters

2. View/Edit Distributions

Process distribution determines the process time each aircraft spends in a procedure. Distributions can be any number of probability distributions used to draw random samples, including exponential, normal, Poisson, triangular, and Weibull. Simio recognizes each distribution as random.Distribution(Parameters). For example, a triangular distribution with minimum of one minute, mode of two minutes, and a maximum of three is read in Simio as random.triangular(1,2,3). Common distributions are;

- exponential(lambda)
- normal(mean, standard deviation)
- Poisson(lambda)

- triangular(min, mode, max)
- Weibull(shape, scale)

We are able to adjust process time by squadron but typically, each squadron experience a similar distribution. Our baseline process times are described in Section J. The form populates with our baseline data as shown in Figure 13. The user can change one row and click the circled button to auto fill data for the remaining squadrons.

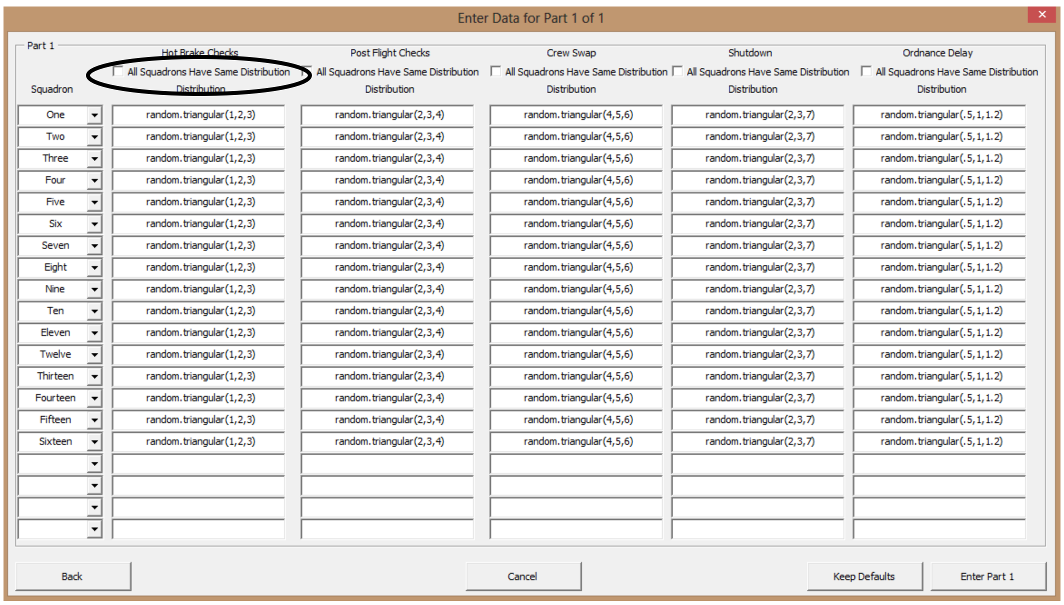

Figure 13. User interface to enter stochastic process times for each squadron.

3. Process Schedule

The user first inputs $Squadron, AC_x, \mathrm{DS}_{x,w}, \mathrm{AS}_{x,w}$ into the spreadsheet *EnterAirPlan*, then presses the process schedule button. Then, a Visual Basic for Applications (VBA) coding sequence is initiated that adds additional parameters AC_{type}, $Priority$, BS_x, and $Lead$ to the air plan, and then columns are copied to the *DailyAirPlan* spreadsheet where they are tabled ($Wave_x$ is discussed in the following section). The wave one data is copied to the *WaveOne* spreadsheet for use in the source object in Simio to create aircraft in the model. The *CombinedSched* spreadsheet is populated with the *DailyAirPlan* data parsed by squadron, essentially recreating each squadron's flight schedules which are used to schedule all subsequent waves. An example daily air plan sorted by departure time and squadron is shown in Table 6.

Squadron	ACx	DSx	ASx	Priority	Wave	BSx	Lead
One	1	01/01/2013 08:30 AM	01/01/2013 10:00 AM	1	1	1	1
One	1	01/01/2013 09:00 AM	01/01/2013 10:00 AM	2	1	1	1
Six	3	01/01/2013 09:00 AM	01/01/2013 10:30 AM	40	1	2	1
Six	3	01/01/2013 09:00 AM	01/01/2013 10:30 AM	40	1	2	2
Six	3	01/01/2013 09:00 AM	01/01/2013 10:30 AM	41	1	2	1
Six	3	01/01/2013 09:00 AM	01/01/2013 10:30 AM	41	1	2	2
Eleven	4	01/01/2013 09:00 AM	01/01/2013 10:45 AM	70	1	2	1
Eleven	4	01/01/2013 09:00 AM	01/01/2013 10:45 AM	70	1	2	2
Eleven	4	01/01/2013 09:00 AM	01/01/2013 10:45 AM	71	1	2	1
Eleven	4	01/01/2013 09:00 AM	01/01/2013 10:45 AM	71	1	2	2
Fourteen	1	01/01/2013 09:15 AM	01/01/2013 10:30 AM	88	1	2	1
Fourteen	1	01/01/2013 09:15 AM	01/01/2013 10:30 AM	88	1	2	2
Fourteen	1	01/01/2013 09:15 AM	01/01/2013 10:30 AM	89	1	2	1
Fourteen	1	01/01/2013 09:15 AM	01/01/2013 10:30 AM	89	1	2	2
One	3	01/01/2013 09:30 AM	01/01/2013 11:00 AM	3	1	2	1
One	3	01/01/2013 09:30 AM	01/01/2013 11:00 AM	3	1	2	2
Nine	1	01/01/2013 09:30 AM	01/01/2013 11:00 AM	64	1	2	1
Nine	1	01/01/2013 09:30 AM	01/01/2013 11:00 AM	64	1	2	2
Sixteen	3	01/01/2013 09:30 AM	01/01/2013 10:45 AM	102	1	2	1
Sixteen	3	01/01/2013 09:30 AM	01/01/2013 10:45 AM	102	1	2	2
One	3	01/01/2013 10:00 AM	01/01/2013 11:30 AM	4	1	4	2
One	3	01/01/2013 10:00 AM	01/01/2013 11:30 AM	4	1	4	2
Two	4	01/01/2013 10:00 AM	01/01/2013 11:30 AM	19	1	2	1
Two	4	01/01/2013 10:00 AM	01/01/2013 11:30 AM	19	1	2	2
Two	4	01/01/2013 10:00 AM	01/01/2013 11:30 AM	20	1	2	1
Two	4	01/01/2013 10:00 AM	01/01/2013 11:30 AM	20	1	2	2
Five	4	01/01/2013 10:00 AM	01/01/2013 10:45 AM	35	1	2	2
Ten	1	01/01/2013 10:00 AM	01/01/2013 11:30 AM	67	1	2	1
Ten	1	01/01/2013 10:00 AM	01/01/2013 11:30 AM	67	1	2	2
Seven	1	01/01/2013 10:30 AM	01/01/2013 12:00 PM	49	1	2	1
Seven	1	01/01/2013 10:30 AM	01/01/2013 12:00 PM	49	1	2	2

Table 6. Sample daily air plan ready to be imported into Simio.

L. OUTPUT

Once the air plan and parameters are saved in Excel, the user can proceed to Simio to run the model. The Simio file must be saved in the same directory as the excel file. Upon pressing run, input data is uploaded automatically through the use of user defined dynamic-link library (DLL) "ExcelRead" and "ExcelWrite" files. Output data is automatically saved in comma separated values (CSV) file. The two metrics we chose to analyze are average idle time, $TEO_{x,w}$, and the percentage of flights refueling at the hot skids, $PercentSkids$.

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IV. RESULTS

In this chapter we introduce results from our base model, experiment with policy recommendations that reduce processing times at bottleneck processes, and then compare the results of each experiment with our baseline model. We experiment with a potential method of both increasing sortie production and decreasing hot skid use by temporarily reallocating aircraft through the use of detachments (det's). We present our findings in terms of fuel and maintenance cost saved per year if implemented at Oceana and Lemoore alone. Resulting figures would be significantly higher if fully burdened fuel cost were included (Truckenbrod, 2010). We conclude by examining a single engine ground operations policy that could significantly reduce fuel consumption on the flight line.

A. INTRODUCTION

Air ENCON seeks to achieve a 4% reduction in non-mission fuel burn in aviation by 2020 without adversely affecting mission execution or safety. Our goal in this thesis is to find squadron-level efficiencies and bridge the gap between tactical and institution-wide recommendations. To this end, we collected data from training squadrons, fleet squadrons, U.S. Atlantic and Pacific Fleet Commands, fuels managers, supply officers, and Air Traffic Controllers at Oceana and Lemoore to determine how processes compare across bases and to examine differences and determine if policy changes could be instituted across bases. An additional benefit is that we also discovered base-specific changes that have a significant impact for operations at that base.

We conducted experiments utilizing eight potential policy changes. The first three changes involve the hot brake check process, and the remaining four involve aircraft refueling. We also explored inefficiencies in allocation of aircraft across bases. We experiment with potential detachments of aircraft and flight instructors from Oceana's VFA-106 training squadron to Lemoore's VFA-122 training squadron for the benefit of overall fleet health.

B. BASE MODEL

We first developed our base model to determine our baseline idle fuel burn and identify where queues build in the network. We use baseline process time distributions developed through data collection and subject matter expert guidance (presented in detail in Chapter III). We generate aircraft using empirical flight schedules collected from Oceana and Lemoore rather than samples from an input probability distribution, which results in a statistically more precise comparison to the real system (Law, 2007). Schedules are replicated 100 times with varying random number seeds in order to generate 95% confidence intervals (CI). We indicate results in percent queue time because absolute time depends on the scale of operations. Our results indicate that queues build in the hot brake check and hot skid process areas much more than in any other post-flight process. In fact, close to 75% of all queues occur in these two processes as shown in Table 7. With the hot brake check and hot skids accounting for such a large majority of idle time, we focus on finding process improvements in these two areas.

Percent of Queue Time at Each Process			
NAS Lemoore		**NAS Oceana**	
Hot Skids	54%	Hot Brake Check	41%
Hot Brake Check	28%	Hot Skids	32%
Marshal	11%	Marshal	18%
Post Flight Checks	5%	Post Flight Checks	7%
Crew Swap	1%	Crew Swap	1%
Engine Shutdown	<1%	Engine Shutdown	<1%
Engine Start	<1%	Engine Start	<1%

Table 7. Percent of queue time spent in each process in base model.

Our results indicate that aircraft average idle time, or time spent with engines online during post-flight operations, is 25:24 at Oceana and 21:12 at

Lemoore, as shown in Figure 14. The percent of aircraft refueling at the hot skids is 12.4% at Oceana and 20.6% at Lemoore as shown in Table 8.

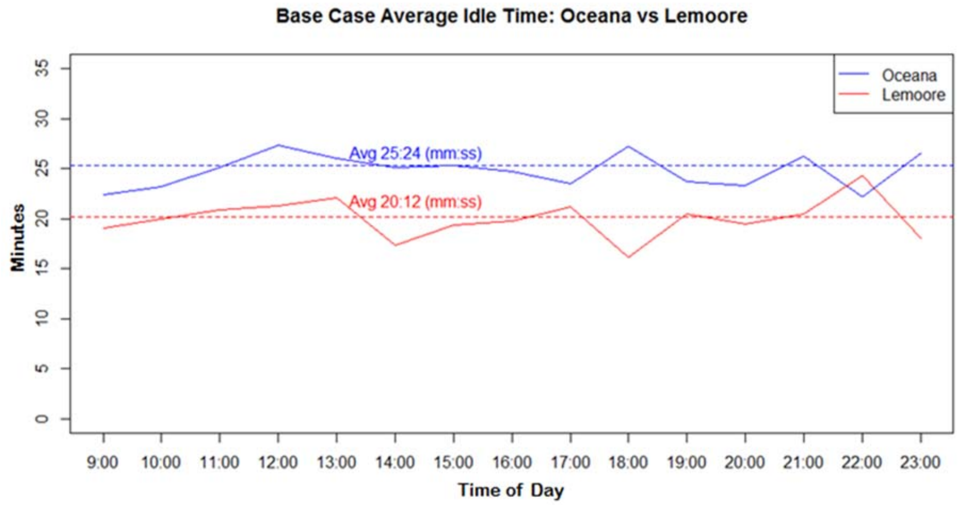

Figure 14. Base case average idle time by time of day.

Baseline Average Idle Time ($TEO_{x,w}$) and Percent Hot Skid Use				
	NAS Lemoore		NAS Oceana	
	Idle Time (mm:ss)	Percent Skids	Idle Time (mm:ss)	Percent Skids
Mean	21:12	20.6%	25:24	12.42%
95% confidence interval	+/- 22 sec	+/- .25 sec	+/- 35 sec	+/- .11 sec
Standard deviation	4.65	0.11	6.92	0.09
Median	21:00	20.61%	24:30	12.4%

Table 8. Baseline average idle time per aircraft and percentage of aircraft refueling at hot skids.

C. EXPERIMENTS

1. Reduced Hot Brake Check

Two procedures that occur in the hot brake check can be moved to the squadron line; those are degaussing the aircraft and covering the CATM-9 seeker head. Degaussing must occur prior to the aircrew exiting the aircraft and can be conducted in the post-flight process area in the squadron line. Covering the CATM-9 seeker head at the hot brake check area is a carryover technique from when CATM-9's had a safety switch that was required to be safed immediately after landing. The current CATM-9 version no longer has this switch. In addition, the process time of conducting the hot brakes can be reduced by utilizing a laser gun to check brake temperature rather than using the back of hand technique. The laser gun is not only quicker and more efficient, it is also safer.

We estimate that moving the degauss process to the line and processing aircraft via the laser gun instead of the back of the maintainers hand will reduce processing time by 30 seconds from triangular (1,2,3) to triangular (.5,1.5,2.5). Covering the CATM-9 seeker head occurs only if the aircraft is carrying ordnance. In our baseline model aircraft carry ordnance on 65% of flights. On those flights with ordnance ($ORD = 1$) processing time at the hot brake checks increases to include ordnance de-arm, represented as triangular (.5,1,1.2) in the base model. We estimate that covering the CATM-9 seeker head in the line will reduce ordnance de-arm processing time by 30 seconds to triangular(0,.5,.7). Thus, the complete processing time of hot brake check is reduced from $\text{triangular}(1,2,3) + ORD * \text{triangular}(.5,1,1.2)$ to $\text{triangular}(.5,1.5,2.5) + ORD * \text{triangular}(0,.5,.7)$. When we compare our reduced hot brake check model to the base case, we see a 30-second reduction in average idle time at Lemoore and a 72-second reduction at Oceana as shown in Table 9. The confidence intervals overlap slightly in both the Lemoore and Oceana experiment. We ran a t-test comparing the means of the times for the base model and reduced hot brake model in both cases, with the null hypothesis that the means are equal and the alternative hypothesis that they are not equal.

$$H_o : \mu_{Base} = \mu_{ReducedBrake}$$
$$H_a : \mu_{Base} \neq \mu_{ReducedBrake}$$
$$\text{Lemoore}: p - value = .046 \qquad \therefore \text{ Reject the null}$$
$$\text{Oceana}: p - value = .014 \qquad \therefore \text{ Reject the null}$$

The p-values indicate that there is a statistically significant difference in the means of the base model and the reduced hot brake model and we therefore reject the null.

Average Idle Time per Aircraft (mm:ss)				
	NAS Lemoore		NAS Oceana	
	Base Model	Reduced Hot Brake	Base Model	Reduced Hot Brake
Mean	21:12	20:42	25:24	24:12
95% confidence interval	+/- 22 sec	+/- 21 sec	+/- 35 sec	+/- 42 sec
Standard deviation	4.65	4.56	6.92	7.1
Median	21:00	20:42	24:30	23:00
Average reduction in idle time	*30 seconds*		*72 seconds*	

Table 9. Average reduction in idle time by reducing process time at hot brake checks.

2. Smart Refueling

We experimented with potential policy changes relating to the aircraft refueling process. The first two variations involve improving the flow of information to the fuels division. The fuels divisions at Oceana and Lemoore are given the air plan the night before operations. While the fuels manager can determine the expected arrival times of aircraft from the schedule, he or she still does not know which aircraft will require hot skids or fuel trucks and whether the aircraft are returning on time. As mentioned in Chapter III, Section J, there are significant variations in actual arrival times around scheduled times. A lack of quality information prevents fuel managers from being able to manage fuel trucks and personnel efficiently. We reflect the current reactive system by simply not dispatching trucks until aircraft have entered the engine shutdown process and, in the case of Lemoore, have entered the hot skids.

In addition, information exchange between squadrons and fuels division is an area where easy improvements can be made. The flow of information can be increased by annotating known hot skid turnarounds on the flight schedule by marking “HS” in the notes section. Squadrons typically know when particular flights are going to require hot skid refueling, but there is no indication of such evolutions on any documents given to the fuels department. Fuel divisions could pre-position trucks, make better decisions on when to refill the fuel truck tank and allocated personnel more effectively to cover expected busy periods.

The quality of information can be increased by practicing more of a just-in-time demand request for fuel trucks by requesting fuel trucks at the moment they are needed and not before. The process of requesting a fuel truck is first initiated through the 10 minute out, or blue line, call. The 10 minute out call is the radio call from the inbound aircrew to the squadrons' maintenance control. Maintenance control then relays the message to fuels division, which then dispatches a truck. The call is intended to be initiated 10 minutes prior to when the aircraft is expected to be shut down in the line. However, aircrew often make this call early, late, or fail to make it at all, leading to inefficiencies in fuel truck operations and unnecessary delays.

We experiment with a smart fuel-truck routing process that assumes the fuels division has increased awareness of intentions and higher quality of information by adjusting the following:

- Allow fuel trucks to refuel the fuel truck tank at saddle points in the flight schedule
- Always refuel fuel truck prior to returning to dispatch
- Preposition full fuel trucks at squadron hangars

Our results indicate that by increasing the quantity and quality of information provided to the fuels division, we are able to reduce average idle time by 24 seconds at Lemoore and 6 seconds at Oceana as shown in Table 10.

Average Idle Time per Aircraft (mm:ss)				
	NAS Lemoore		NAS Oceana	
	Base Model	Smart Refueling	Base Model	Smart Refueling
Mean	21:12	20:48	25:24	25:18
95% confidence interval	+/- 22 sec	+/- 21 sec	+/- 35 sec	+/- 30 sec
Standard deviation	4.65	4.87	6.92	6.82
Median	21:00	20:53	24:30	24:42
Average reduction in idle time	*24 seconds*		*6 seconds*	

Table 10. Average reduction in idle time by increasing quantity and quality of information provided to fuels division.

Using a t-test, we compare the means of the base model to the smart refueling model. We fail to reject the null hypothesis at the .05 level. However, there is significance at the .1 level.

$$H_o : \mu_{Base} = \mu_{SmartFueling}$$
$$H_a : \mu_{Base} \neq \mu_{SmartFueling}$$
$$\text{Lemoore}: p - value = .1 \qquad \therefore \text{ Fail to reject the null}$$
$$\text{Oceana}: p - value = .86 \qquad \therefore \text{ Fail to reject the null}$$

We conclude that there is marginal significance in executing smart refueling at Lemoore. A reduction in average idle time of 6 seconds at Oceana is not statistically significant. However, common sense implies that implementing smart refueling policy will not adversely affect operations and may have additional benefits not captured in our metric, such as reducing fuels division man-hours. Potential factors affecting our output of the Oceana model are the additional fuel trucks at Oceana (15 vs 10), Oceana's fuel truck refueling policy (always refueling the truck prior to returning to dispatch), and the fact that fuel trucks aren't required at hot skids refuels. This topic warrants further research but is beyond the scope of this thesis.

3. No fuel trucks required

The hot skid process is conducted slightly differently between bases. At Lemoore, a fuel truck driver is required to operate the safety switch, or "dead" switch, when hot skids are in use. The fuel truck driver parks the fuel truck next to the hot skids during the refueling execution. Therefore, requirements for hot skid refueling include squadron maintainers, a fuel truck and a fuel truck driver. To be clear, a fuel truck driver can operate the "dead" switch for parallel hot skids so if side-by-side hot skids are in use, only one truck is being utilized.

At Oceana, squadron maintainers are responsible for the safety switch, freeing up the fuel truck to conduct its primary mission. Our base models accounts for the differences in requirements. We wanted to determine whether requiring a fuel truck driver at the hot skids caused an increase in idle time at Lemoore. We experiment with a policy change of allowing squadron maintainers to operate the "dead" switch by removing the requirement of a fuel truck for hot skid operation. We estimate that the new policy would reduce average idle time by 48 seconds at Lemoore as shown in Table 11.

Average Idle Time per Aircraft (mm:ss)		
	NAS Lemoore	
	Base Model	No Truck Req.
Mean	21:12	20:24
95% confidence interval	+/- 22 sec	+/- 38 sec
Standard deviation	4.65	4.34
Median	21:00	19:50
Average reduction in idle time	*48 seconds*	

Table 11. Average reduction in idle time by eliminating the requirement of a fuel truck operator during hot skids refuels.

We compare the means of the base model to the no truck required model in a t-test. We reject the null hypothesis at the .05 level with a p-value of .034. Therefore, we conclude that there is a statistically significant difference in the means of the two models, resulting in an average improvement of 48 seconds.

$$H_o : \mu_{Base} = \mu_{NoTruckReq}$$
$$H_a : \mu_{Base} \neq \mu_{NoTruckReq}$$
$$\text{Lemoore}: p - value = .034 \qquad \therefore \text{ Reject the null}$$

4. Experiments Containing All Recommendations

Savings are not purely additive if all policy recommendations are put in place. However, we see the best results when all recommendations are included in the model. We incorporate all recommendations into the models and compare the output of four weeks of air plans to that of the base model. Results indicate a 72-second average reduction in idle time at Lemoore and a 78-second average reduction in idle time at Oceana as shown in Table 12. This equates to 250,920 gallons of fuel at a saving of $8,113,392 in fuel and maintenance at Oceana and Lemoore alone.

Average Idle Time per Aircraft (mm:ss)				
	NAS Lemoore		NAS Oceana	
	Base Model	All Recommendations	Base Model	All Recommendations
Mean	21:12	20:00	25:24	24:06
95% confidence interval	+/- 22 sec	+/- 24 sec	+/- 35 sec	+/- 40 sec
Standard deviation	4.65	4.47	6.92	7.03
Median	21:00	20:00	24:30	23:06
Average reduction in idle time	*72 seconds*		*78 seconds*	

Table 12. Average reduction in idle time with all recommendations in place.

We compare the means of the base model to that of the model with all our all recommendations included using a t-test. We reject the null hypothesis at the .05 level with a p-value of .001 for Lemoore and .005 for Oceana. Therefore, we conclude that there is a statistically significant difference in the means in both cases.

$$H_o : \mu_{Base} = \mu_{AllRecommendations}$$
$$H_a : \mu_{Base} \neq \mu_{AllRecommendations}$$
$$\text{Lemoore}: p-value = .001 \qquad \therefore \text{ Reject the null}$$
$$\text{Oceana}: p-value = .005 \qquad \therefore \text{ Reject the null}$$

5. Detachments of Aircraft

Our data collection efforts revealed a marked difference in production of replacement pilots between the fleet replacement squadrons (FRS) VFA-106 and VFA-122, located at Oceana and Lemoore respectively. Replacement pilots at Lemoore are currently taking 54 weeks to complete a 38 week training program, whereas Oceana students are averaging approximately 40 weeks to complete training. One of the leading factors contributing to the extended time to train at Lemoore is a low rft aircraft rate which is currently around 17%. Oceana's rft is close to 35%. The difference in rft rates is an interesting topic in and of itself but is beyond the scope of this thesis. When students take longer to train, time between events increases leading to less proficiency and an increase in the number of warm-up flights required. From a financial standpoint, warm-up flights are a wasted cost. We wanted to determine whether changing aircraft allotments could reverse the current trend at Lemoore to begin reducing time to train.

a. Number of Flights per Day

Data collected in the 2014 F/A-18 Training Requirements Letter and the current category I-V syllabus requirements indicate an average of 30,557 flights are required each year to maintain student production as shown in Table 13.

Total Number of Flights Required per Year (Both Bases Combined)					
	CAT-I (C/D)	CAT-I (E/F)	CAT-II & III	CAT-IV	CAT-V
Number of Students	22	138	103	185	67
Number of Flights per Student (including support)	135	127	83	6	6
Number of Flights per Year	2,970	17,526	8,549	1,110	402
Total Number of Flights per Year	30,557				

Table 13. Total number of flights required per year, including flight support (e.g., flight lead and bandit support).

We assume 45% of flight students train at Lemoore and 55% of students train at Oceana. As shown in Table 14, a 45/55 student split results in Lemoore requiring 55 flights per day and Oceana requiring 67 flights per day in order to maintain student production.

Average Number of Flights per Day (45/55 Student Split)		
	NAS Lemoore	NAS Oceana
Number of Students	206	309
Avg Num of Flights per Student (including support)	59.3	59.3
Total Number of Flights per Year	13,751	16,806
Average Number of Flydays per Year	250	250
Average Number of Flights per Day	55	67

Table 14. Average number of flights required per day at Oceana and Lemoore in order to sustain student production.

b. Number of Aircraft Available

We calculate rft aircraft based on current rft rates of 17% and 35% for Lemoore and Oceana respectively. We use an estimated total number of aircraft of 70 per training squadron, resulting in Lemoore having 12 aircraft available to fly on average and Oceana having 24 aircraft as shown in Table 15.

Ready For Tasking (RFT) Aircraft		
	NAS Lemoore	NAS Oceana
Number of Aircraft	70	70
RFT Rates	0.17	0.35
RFT Aircraft Available to Fly	*12*	*24*

Table 15. Ready for tasking (rft) aircraft available to fly per base.

c. Number of Events per Aircraft

We assume that the number of flights each aircraft can fly is dependent on the type of refueling conducted between flights. Hot skids refueling produces a shorter turnaround time and therefore an aircraft that refuels at the hot skids can launch in a compressed timeline compared to an aircraft using fuel truck refueling. For our analysis, we assume an aircraft can fly four events per day if the hot skids are used in at least one wave. An aircraft can fly three events per day if fuel trucks exclusively, written in notation as $\mathrm{NumberOfEvents}_x = \{(4 \mid \mathrm{NumOf\ HotSkids}_x > 0) \cap (3 \mid \mathrm{NumOfHotSkids}_x = 0)\},\ \forall x$, where $\mathrm{NumberOfEvents}_x$ is the number of waves each aircraft *x* can fly, and $NumOfHotSkids_x$ is the number of hot skids refuels for aircraft *x*. Intuitively, squadrons are inclined to use hot skids if unable to support production requirements because the aircraft can fly another event. We believe this to be a primary reason why Lemoore's hot skid usage rate is 27% and Oceana's is approximately 10%.

d. *Effects of a Det*

Using the assumptions described in sections a through c, we are able to determine the number of sorties and percentage of hot skids refuels as a function of the number of rft aircraft. The training squadrons' primary objective is sortie production. In our case, Oceana and Lemoore must attain 67 and 55 flights per day, respectively, in order to meet production requirements, shown in the grey region in Figure 15. Each aircraft is utilized to its full capacity until production requirements are met, i.e., all available aircraft will refuel at the hot skids (at least once) in order to increase the number of events flown by that aircraft from 3 to 4. In this region, every aircraft refuels once at the hot skids and three times via the fuel truck, making percent of skids 25%. This continues as aircraft are added until 55 and 67 events, respectively, are achieved. At that time, squadrons begin to allow aircraft to refuel solely at the hot brakes. As we move in the grey region from left to right, more aircraft are added, allowing for less demand per aircraft, i.e., more aircraft using three fuel truck evolutions and zero hot skids. This trend continues until all aircraft are using fuel trucks. The vertical dashed line indicates the current position of Oceana and Lemoore. Ideally, we would like to see both squadrons in the grey region and using 0% hot skids.

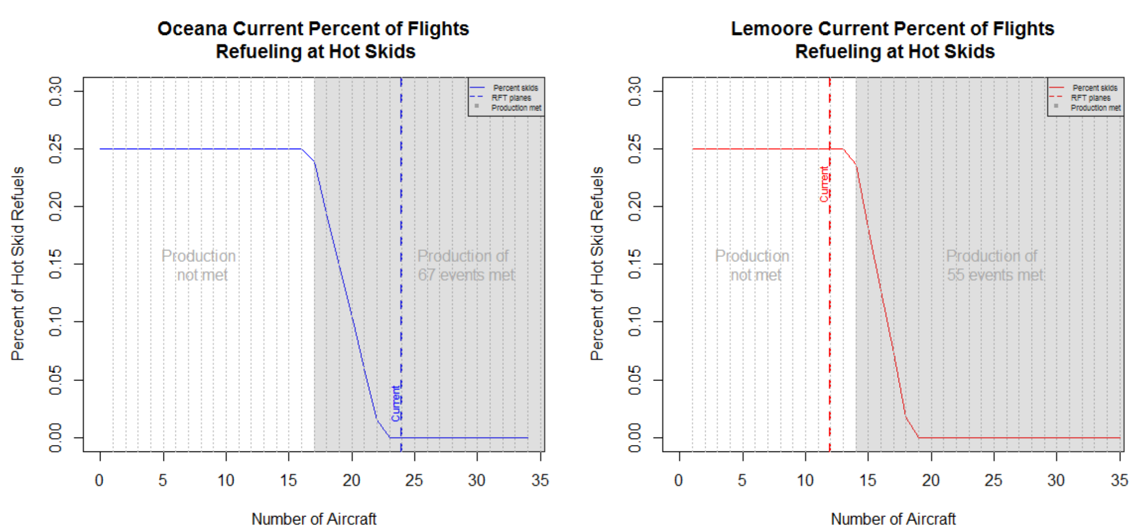

Figure 15. Current percent of flights refueling at hot skids at Oceana and Lemoore.

We combine all aircraft available and look at the problem from a macro level to determine the appropriate det size in Figure 15. The bottom left corner of the X axis indicates the state where Oceana has all 36 rft aircraft and Lemoore has none. In this state, Oceana meets full production requirements and Lemoore produces nothing. Each step from left to right is interpreted as moving one plane from Oceana to Lemoore. Leading to the opposite extreme in the bottom right axis, where Lemoore has all the aircraft. The current rft aircraft per squadron of 12 and 24 are indicated by the vertical dashed lines labeled “current.” Figure 16 is reproduced by folding Figure 15 in half, placing the two plots on top of each other.

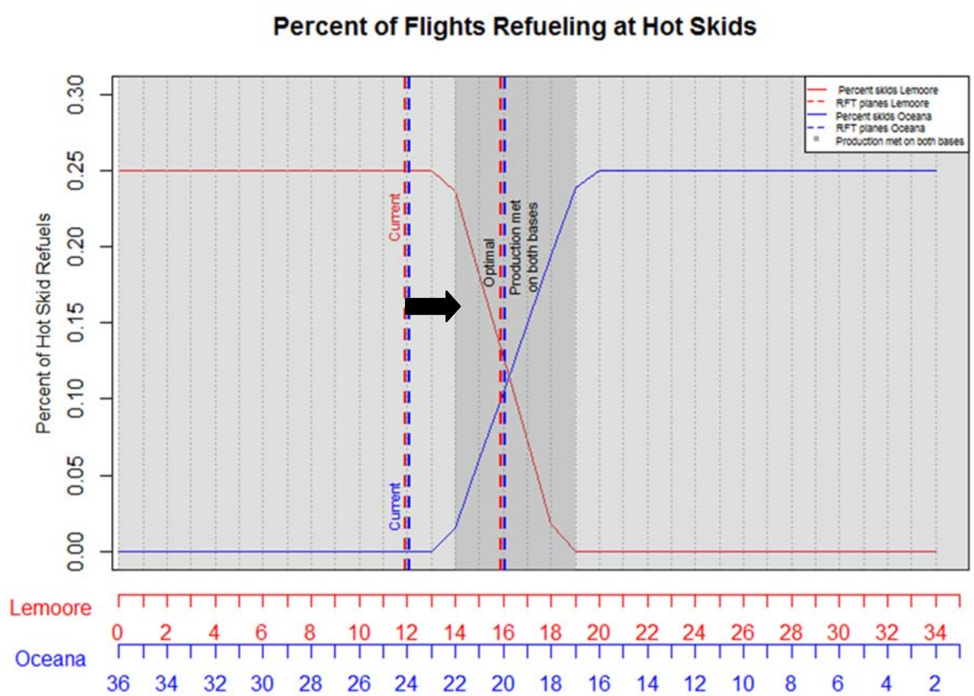

Figure 16. Number of aircraft allocated per training squadron to achieve optimal reduction in hot skids while still reaching flight requirements.

Based on trends observed between February and May 2014, we estimate a det of 2–4 aircraft for a two week period will increase the sortie rate at Lemoore from 48 to 55 sorties without decreasing the rate at Oceana. When we experiment with our det scenario in our simulation, the overall percentage of hot skids refueling is reduced by 5.7% as shown in Table 16.

Percent of Flights Refueling at Hot Skids		
	NAS Lemoore	NAS Oceana
Base Model	20.6%	12.4%
4 Aircraft Det (Oceana to Lemoore)	14.9%	12.7%
Total Reduction of Hot Skids	5.7%	

Table 16. Aggregate reduction in percentage of hot skids with a four aircraft det from Oceana to Lemoore.

In our analysis, we hold rft rates constant, essentially creating a snapshot of operations at Oceana and Lemoore. In reality, rft rates are closely tracked metrics that continually change. Nevertheless, this model can be useful when diametrically opposed trends between training squadrons are observed. Negative trends in rft at one training squadron can be controlled and reversed by dets when the opposite squadron is healthy. Det's have the additional benefits of increasing standardization of training, reducing the standard deviation of time to train, and decreasing the number of warm-up flights required due to lack of aircraft. In order to avoid the flaw of linear thinking, this policy should be readdressed periodically as rft rates and student loading change over time.

D. SINGLE ENGINE POST FLIGHT PROCESSING POLICY

Aircraft with multiple engines often conduct ground operations with a reduced number of engines online in order to conserve fuel. Reduced engine operations can occur in both preflight and post-flight operations, both of which are common policy in the commercial airline industry. Tactical military aircraft have not adopted these policies and little research has been done to address the cost benefit of doing so. Policies that incorporate single-engine preflight operations must take into account the possibility of maintenance issues caused by changing engine configurations closer to departure time and in areas of the flight line without maintenance. We did not collect data in this area during our research and therefore do not attempt to model a preflight single-engine policy.

However, our simulation allows us to experiment with single-engine post-flight policies with only minor adjustments to the model and the benefits of doing so may prove fruitful with follow-on research.

For this experiment, we chose to implement a single-engine post-flight policy where aircraft shut off an engine after safely exiting the runway. We create two measures of effectiveness (MOE) by splitting $TEO_{x,w}$ MOE into $TaxiTEO_{x,w}$ and $IdleTEO_{x,w}$. $TaxiTEO_{x,w}$ records the time an aircraft spends with both engines online (as when exiting the runway) and the remainder of the time that the aircraft is taxiing (regardless of dual or single engine). We assume an aircraft requires the same amount of thrust whether one or both engines are online while taxiing. Therefore, the total fuel burn rate is the same for single engine or dual engine while taxiing (i.e., a single engine aircraft must produce double the output of each engine in a dual engine aircraft). $IdleTEO_{x,w}$ records the time an aircraft spends with one engine online while static, either in queue or in processing at a station. In relation to our baseline model, $TEO_{x,w} = TaxiTEO_{x,w} + IdleTEO_{x,w}$. The fuel and cost saving benefit is realized in the difference in fuel burn rate and cost per minute between $TaxiTEO_{x,w}$ and $IdleTEO_{x,w}$, as shown in Table 17.

Cost Metrics: Dual Engine vs. Single Engine								
	Dual Engine & Single Engine Taxiing ($TEO_{x,w}$)				**Single Engine Idling ($SingleTEO_{x,w}$)**			
	gallons per min (gpm)	**fuel cost per min**	**maint cost per min**	**total cost per min**	**gallons per min (gpm)**	**fuel cost per min**	**maint cost per min**	**total cost per min**
F/A-18 C/D	2.94	$10.71	$100.00	***$110.71***	1.47	$5.36	$50.00	***$55.36***
F/A-18 E/F	3.64	$13.38	$100.00	***$113.38***	1.82	$6.69	$50.00	***$56.69***

Table 17. Difference in cost between dual engine and single engine operations.

We use four weeks of flight schedules at Lemoore and Oceana to determine the percentage of F/A-18 C/D and F/A-18 E/F flights to create weighted gpm and costs per base, as shown in Table 18. At Lemoore, 29/71% of flights from 1 March, 2014 to 31 March, 2014 were flown by Legacy and Super

Hornets, respectively. At Oceana, 42/58% of flights from 1 May, 2014 to 31 May, 2014 were flown by legacy and Super Hornets, respectively.

Weighted MOE's at Lemoore and Oceana				
	Dual Engine & Single Engine Taxiing		Single Engine Idling	
	NAS Lemoore	NAS Oceana	NAS Lemoore	NAS Oceana
Percent legacy/super hornet flights (%)	29/71	42/58	43/57	42/58
Weighted gallons per minute (gpm)	3.44	3.36	1.72	1.67
Weighted fuel & maint cost per min	$112.61	$112.26	$56.30	$56.13

Table 18. Weighted gallons per minute (gpm) and cost per minute for dual and single engine operations.

We compare the output produced by four weeks of air plans in the single-engine policy model to that of the baseline model. Our results indicate that implementing a single-engine policy would reduce the average amount of time aircraft spend with both engines online from 21:12 (mm:ss) to 6:55 $\pm$ 32 seconds with 95% confidence at Lemoore and reduce dual engine time from 25:24 to 8:41 $\pm$ 41 seconds with 95% confidence at Oceana, as shown in Table 19.

Average Reduction of Time Spent with Both Engines Online in Post Flight Operations (mm:ss)		
	NAS Lemoore	NAS Oceana
Average taxi time/dual engine ($TaxiTEO_{x,w}$)	6:55	8:41
Average idle time/single engine ($IdleTEO_{x,w}$)	14:16	16:43
Total Time ($TEO_{x,w}$)	21:12	25:24
Percentage of Time Spent Single Engine	*67.4%*	*65.8%*

Table 19. Average reduction in dual engine time.

If implemented, our results indicate that two-thirds of all time spent on deck could be with one engine shut off. We use a conservative estimate of 110 and 120 flights per day at Lemoore and Oceana and 250 fly days per year to create Table 20 (Gerber & Clark, 2013).

Total Number of Minutes per Year in Ground Operations: Baseline vs Single Engine Policy (mm:ss)						
	Baseline Model		Single Engine Policy			
	NAS Lemoore	NAS Oceana	NAS Lemoore		NAS Oceana	
			Dual Engine/Taxi Time	Single Engine/Idle Time	Dual Engine/Taxi Time	Single Engine/Idle Time
Time	21:12	25:24	6:55	14:28	8:41	16:43
Avg number of flights per day	110	120	110	110	120	120
Avg number of fly days per year	250	250	250	250	250	250
Number of minutes per year	*583,000*	*762,000*	*190,300*	*392,700*	*260,400*	*501,600*

Table 20. Number of minutes per year conducting ground operations, split by dual engine and single engine time.

Our results indicate that single-engine policy reduces ground fuel consumption from a combined total of over 4.5 million gallons at Lemoore and Oceana to just over 3 million gallons for a savings of over 1.5 million gallons per year, as shown in Table 21.

Gallons of Gas Consumed per Year: Baseline vs Single Engine Policy						
	Baseline Model		Single Engine Policy			
	NAS Lemoore	NAS Oceana	NAS Lemoore		NAS Oceana	
			Dual Engine/Taxi	Single Engine/Idle	Dual Engine/Taxi	Single Engine/Idle
Number of minutes per year	583,000	762,000	190,300	392,700	260,400	501,600
Gallons per minute	3.44	3.36	3.44	1.72	3.36	1.67
Gallons of gas consumed per year	2,005,520	2,560,320	654,632	675,444	874,944	837,672
Total gallons of gas consumed	4,565,840		3,042,692			
Total reduction in gallons of gas consumed	*1,523,148 gallons*					

Table 21. Total reduction in fuel consumption per year using single engine ground operations.

Finally, we incorporate our weighted average fuel and maintenance cost from Table 18 with dual- and single-engine time resulting in Table 22. We estimate that policy would save over $22 million at Lemoore and over $28 million at Oceana for a total of over $50 million in savings per year at these two bases alone.

Total Cost Savings per Year: Baseline vs Single Engine Policy						
	Baseline Model		Single Engine Policy			
	NAS Lemoore	NAS Oceana	NAS Lemoore		NAS Oceana	
			Dual Engine/Taxi	Single Engine/Idle	Dual Engine/Taxi	Single Engine/Idle
Number of minutes per year	583,000	762,000	190,300	392,700	260,400	501,600
Weighted avg cost per min (fuel & maint cost)	$112.61	$112.26	$112.61	$56.30	$112.26	$56.13
Cost per year	$65,651,630	$85,542,120	$43,538,693		$57,387,312	
Total cost per year	$151,193,750		$100,926,005			
Total savings	*$50,267,745*					

Table 22. Total cost savings per year of a single engine ground operations policy at Lemoore and Oceana.

When looked at from a fuel savings perspective, there is an enormous opportunity to reduce fuel consumption by implementing a single engine ground policy. The majority of mission and safety requirements, if not all, are complete by the time an aircraft exits the runway following a flight. However, we are not in a position to recommend or rule out single-engine post-flight policies due to the fact that we have not conducted thorough research on safety and readiness concerns unique to tactical aircraft. Further research should be conducted in this area to capture the full cost-benefit analysis.

V. CONCLUSION

We recommend eight policy changes be adopted by NAS Lemoore and Oceana. The first two recommendations involve the hot brake check. Two procedures that often occur in the hot brake check can be moved to the squadron line; those are degaussing the aircraft and covering the CATM-9 seeker head. Degaussing must occur prior to the aircrew exiting the aircraft and therefore can be conducted in the post flight process area in the squadron line. Covering the CATM-9 seeker head at the hot brake check area is a carryover technique from when CATM-9's had a safety switch that was required to be safed immediately after landing. The current CATM-9 version no longer has this switch and therefore, this procedure can be moved to the squadron line area as well. The third recommendation is to utilize a laser gun to check brake temperature rather than using the back of hand technique. The laser gun is not only quicker and more efficient, it is also safer. By implementing these three policy recommendations, we estimate a 72 ± 21 second reduction in average idle time with 95% confidence at Oceana, and a 30 ± 42 second reduction in average idle time with 95% confidence at Lemoore.

Policy recommendations four through six increase the quantity and quality of information being passed from squadrons to the fuels division. Recommendations four and five are simple; always refuel the last flight with fuel trucks and be vigilant in making 10 minute out calls at 10 minutes out. Turnaround time is not critical for the last wave of aircraft returning to base and, when given prior notice, fuel trucks have ample opportunity to refuel prior to the next day's events. The 10 minute out call is intended to be initiated 10 minutes prior to when the aircraft is expected to be shut down in the line. However, aircrew often make this call early, late, or fail to make it at all, leading to inefficiencies in fuel truck operations and unnecessary delays. Policy recommendation six is to annotate known hot skid turnarounds by marking "HS" in the notes section of the flight schedule. Currently, there is no indication of known hot skid evolutions on any documents given to the fuels division. If fuel managers were given an indication as to which flights will require a fuel truck and which time periods would be busiest, they could allocate drivers more efficiently and even pre-position trucks. Our results indicate that by increasing the quantity and quality of information provided to the fuels division, we are able to reduce average idle time by 24 $\pm$ 21 seconds with 95% confidence at Lemoore and 6 $\pm$ 30 seconds with 95% confidence at Oceana.

Our seventh policy recommendation involves operations specific to Lemoore. Allow squadron maintainers to operate the “dead” switch at the hot skids in order to prevent aircraft from having to wait at the hot skids for a fuel truck driver to arrive. This policy also frees the fuels truck driver to service more aircraft. We estimate that the new policy would reduce average idle time by 48 $\pm$ 38 seconds with 95% confidence at Lemoore.

Finally, our eighth recommendation is to organize periodic detachments (det’s) of aircraft and instructor pilots from VFA-106 (located in Oceana) to VFA-122 (located in Lemoore). With a small det of aircraft we are able to increase the production capabilities at Lemoore without effecting training requirements at Oceana. Det’s have side benefits of increasing standardization of training, reducing the standard deviation of time to train, and decreasing the number of warm-up flights required due to lack of aircraft. We estimate a det of 2–4 aircraft for a two week period will increase the sortie rate at Lemoore without decreasing the rate at Oceana. The det also reduces overall percentage of hot skids refueling by 5.7%. In order to avoid the flaw of linear thinking, this policy should be readdressed periodically as rft rates and student loading change over time.

In our simulation, combining all of our policy recommendations reduces average idle time by 72 $\pm$ 24 seconds with 95% confidence at Lemoore and 78 $\pm$ 40 seconds with 95% confidence at Oceana. Shaving seconds off idle time may not sound like much, but imagine a car sitting at a stop light for 30 seconds. Now imagine that that car burns close to four gallons of gas a minute. With hundreds of cars waiting at lights every day, the number of gallons wasted grows rapidly. So rapidly, in fact, that the aircraft at Oceana and Lemoore burn approximately 327,315 gallons of gas per year simply waiting for the light to turn green. If adopted, we estimate our eight recommendations would reduce fuel consumption by 250,920 gallons of gas, saving the Navy over $8 million in fuel and maintenance costs per year at Oceana and Lemoore alone. If adopted across all fighter bases, savings would be substantially higher.

Finally, we recommend further research be conducted on the cost benefit analysis of single engine ground policies. Our analysis indicates over 1.5 million gallons of gas can be conserved, saving more than $50 million per year at Oceana and Lemoore. This topic should be given an emphasis commensurate with the potential savings that can be realized.

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APPENDIX. RELATED WORK

1. Assign aircraft to events while minimizing use of hot skids

We experimented with an alternate method to assign aircraft to events that did not end up being used in our thesis but is an example of an efficient scheduling tool. Given an empirical schedule and the number of rft aircraft available, we are able to schedule waves in order to meet the flight schedule while minimizing the use of hot skids. We assume all available rft aircraft are used to fill the schedule, and all aircraft can fulfill the mission requirements of each event. Squadron *Min Turn Time*, described in Chapter III, Section K, Table 5) is one hour for this example.

Our data entry follows the same logic as in our thesis (detailed in Chapter III, Section K) of an Excel interface to upload the squadron schedule, VBA coding for processing, and Excel output. However, in order to minimize the use of hot skids, we call on a General Algebraic Modeling System (GAMS) optimization solver. After the schedule is put into the *EnterAirPlanHereToMinSkids* spreadsheet, we initiate a VBA coding sequence that parses the daily air plan $DS_{x,w}$ and $AS_{x,w}$ columns from date format into columns of departure and arrival times, shown in Table 23. The code is initiated when the user presses the *calculate waves* button shown in Table 24. The code populates a lower triangular matrix with the turnaround time between each sortie (turnaround time from sortie A to B is $DS_B - AS_A$. If turnaround time is greater than *Min Turn Time* then there is at least an hour between the two flights, allowing for fuel truck refueling (labeled as preferred). If it is less than the squadrons *Min Turn Time* but greater than 15 minutes, then the flight is feasible but requires hot skids refueling (labeled as feasible). Any turnaround time less than 15 minutes is infeasible.

Daily Air Plan							
Squadron	ACx	DSx	ASx	Priority	Wave	BSx	Lead
One	1	1/1/13 8:00 AM	1/1/13 9:30 AM	1		1	1
One	1	1/1/13 8:30 AM	1/1/13 10:00 AM	2		2	1
One	1	1/1/13 8:30 AM	1/1/13 10:00 AM	2		2	2
One	1	1/1/13 8:45 AM	1/1/13 10:00 AM	3		1	1
One	1	1/1/13 10:30 AM	1/1/13 11:30 AM	4		2	1
One	1	1/1/13 10:30 AM	1/1/13 11:30 AM	4		2	2
One	1	1/1/13 10:45 AM	1/1/13 1:00 PM	5		1	1
One	1	1/1/13 11:00 AM	1/1/13 1:00 PM	6		2	1
One	1	1/1/13 11:00 AM	1/1/13 1:00 PM	6		2	2
One	1	1/1/13 11:30 AM	1/1/13 1:30 PM	7		1	1

Table 23. Example air plan used to populate matrix of flight connections.

(green)	Preferred
(yellow)	Feasable
(white)	Infeasable

Calculate Waves

				Departure of flight X (DSx)									
		DSx	Asx	a	b	c	d	e	f	g	h	i	j
Arrival of Flight X (AS x)	a	8	9.5										
	b	8.5	10	-1									
	c	8.5	10	-1	-1.5								
	d	8.75	10	-0.75	-1.25	-1.25							
	e	10.5	11.5	1	0.5	0.5	0.5						
	f	10.5	11.5	1	0.5	0.5	0.5	-1					
	g	10.75	13.167	1.25	0.75	0.75	0.75	-0.75	-0.75				
	h	11	13	1.5	1	1	1	-0.5	-0.5	-2.16667			
	i	11	13	1.5	1	1	1	-0.5	-0.5	-2.16667	-2		
	j	11.5	13.5	2	1.5	1.5	1.5	0	0	-1.66667	-1.5	-1.5	

Table 24. Example lower triangular matrix of feasible flight connections.

The matrix is read into a GAMS optimization program to find a feasible solution given the number of planes available. We use a generalization of a max flow network problem, called a bounded circulation problem, by adding a constraint of a lower bound on arc flows.

Indices:
i = flight departures
j = flight arrivals

Given data:
t_i = takeoff time of flight i
a_j = arrival time of flight j
d_j = demand for flight j
f_i = fly each flight i only once
$table_{j,i}$ = turnaround time between flights, matrix imported from Excel

$planes$ = number of airplanes available

$c_{j,i}$ = turnaround cost of arriving at j and departing at i

$c_{j,i} = \{(100{,}000 \mid \text{table}_{j,i} < 15) \cap (10 \mid 15 \le table_{j,i} \le 60) \cap (0 \mid table_{j,i} > 60)\}$

Decision variables:

$x_{j,i}$ = aircraft scheduled to fly connection from flight j to i, where $x_{j,i}$ = 1 if plane from j connects flight j to i, and $x_{j,i}$ = 0 if plane from j does not connect flight j to i

z = total turnaround cost

$z = \sum_{j,\text{i}} c_{j,i} x_{j,i}$

Constraints:

Fill demand requirements for each flight j: $\sum_i x_{j,i} \ge d_j$, $\forall j$ (1)

Fly each event i only once: $\sum_j x_{j,i} \le f_i$, $\forall i$ (2)

Objective function: Minimize $\sum_{j,\text{i}} c_{j,i} x_{j,i}$

Start and end nodes in $table_{j,i}$ force flow less than or equal to the number of available aircraft, $planes$. Each sortie is assured to be filled by one and only one aircraft by forcing flow on each flight with constraint (1). We encourage fuel truck refueling by assigning a cost per type of refuel with constraint (2). In our objective, we minimize the cost of flight connections, where a flight connection with an hour or more turnaround time costs nothing, a connection with 15 minutes to 1 hour costs 10 (unitless), and a connection of less than 15 minutes costs 100,000. Note that if the schedule is infeasible based on rft aircraft, our GAMS model will still create a feasible solution, however, the total cost, z, will be greater than 100,000. We allowed this for three reasons:

1. We can determine where the scheduling conflict arose and look for better scheduling options (e.g., varying takeoff and land times by only 15 minutes may make the schedule feasible and often have significant improvements in hot skid usage rates).

2. An infeasible schedule often occurs in the fleet when an aircraft goes down after the schedule is written. This optimization shows which flights would be affected by a reduced number of rft aircraft. It should be noted that we assume that all events have the same priority, when in actuality, there is always a priority decision (e.g., a student scheduled to graduate tomorrow may take precedence over a student ahead of timeline). Priority decisions can be included into our optimization program by assigning negative costs to connect to high priority flights or by forcing $x_{j,i}$ =1 for specific connections.

3. An infeasible schedule can be used in the simulation to analyze how heuristic elements affect a known infeasible schedule.

Due to our thesis swaying from optimization to simulation, we stopped our work in optimal aircraft scheduling. However, improvements in military aircraft scheduling is an area ripe with low hanging fruit. Our example is just one method by which to increase scheduling efficiency but there are many other possibilities requiring more research.

LIST OF REFERENCES

AhmadBeygi S., Cohn A., & Lapp M. (2010). Decreasing airline delay propagation by re-allocating scheduled slack. *Institute of Industrial Engineers Transactions*, *42*(7): 478–489.

Airlines for America. (2014, April 1). Annual and per-minute cost of delays to U.S. airlines. Retrieved from http://www.airlines.org/Pages/Annual-and-Per-Minute-Cost-of-Delays-to-U.S.-Airlines.aspx

Arikan M., Deshpande V., & Sohoni M. (2013). Building reliable air-travel infrastructure using empirical data and stochastic models of airline networks. *Operations Research, 61*(1):45–64. Retrieved from http://pubsonline.informs.org/doi/pdf/10.1287/opre.1120.1146

Chief of Naval Operations. (2012a). Naval air training and operating procedures standardization (NATOPS) flight manual Navy model F/A-18A/B/C/D. Retrieved from https://airworthiness.navair.navy.mil/index.cfm?fuseaction=cProductLibrary.detail&versionid=240

Chief of Naval Operations. (2012b, April 11). Navy aviation squadron lineage and naval aviation command insignia. Retrieved from http://www.fas.org/irp/DODdir/navy/opnavinst/5030_4g.pdf

Creemers, S., & Lambrecht, M. (2008). Healthcare queueing models. Ku Leuven University Faculty of Business and Economics Research Report 0804. Retrieved from https://lirias.kuleuven.be/handle/123456789/164227

Defense Logistics Agency. (2013). Energy standard fuel prices. Retrieved from http://www.energy.dla.mil/customer/standard_prices/Pages/default.aspx

Department of Defense. (2012). Flight information publication (terminal) high altitude United States.St. Louis, MO: National Geospatial-Intelligence Agency.

Department of Defense. (2013). Defense budget priorities and choices, fiscal year 2013. Washington, DC: Pentagon. Retrieved from http://www.defense.gov/pubs/DefenseBudgetPrioritiesChoicesFiscalYear2014.pdf

Dunbar, M., Froyland, G., & Wu, C. (2012). Robust airline schedule planning: minimizing propagated delay in an integrated routing and crewing framework. *Institute of Industrial Engineers Transactions.* 46(2): 204–216. Retrieved from http://dx.doi.org/10.1287/trsc.1110.0395

Federal Aviation Administration. (2014a, March 13). Collaborative Decision Making (CDM). Retrieved from http://cdm.fly.faa.gov/

Federal Aviation Administration. (2014b, March 13). Ground Delay Program (GDP). Retrieved from http://www.fly.faa.gov/flyfaa/usmap.jsp

Gerber, C. A., & Clark, J. A. (2013). More flight less fuel: Reducing fuel burn through ground process improvement (Master's thesis, Naval Postgraduate School). Retrieved from http://calhoun.nps.edu/public/bitstream/handle/10945/34667/13Jun_Gerber_Clark.pdf?sequence=1

Google Inc. (2010). Google Earth (Version 5.1.3534.0411) [Software]. Retrieved from http://www.google.com/earth/download/ge/

Green, L. V., Green, R. A., Giglio, J. F., & Soares, J. (2008, June 28). Using queueing theory to increase the effectiveness of emergency department provider staffing. Retrieved from http://onlinelibrary.wiley.com/doi/10.1197/j.aem.2005.07.034/pdf

Gupta, D. (2007). Surgical suites' operations management. *Production and Operations Management Society (POMS)* Volume 16, Number 6, page 689–700. Retrieved from http://www.isye.umn.edu/labs/scorlab/pdf/ssom.pdf

Kelton, W. D., Smith, J. S., & Sturrock, D. T. (2013). *Simio and simulation*. New York: Springer Verlag.

Klabjan, D., Johnson E.L., Nemhouser G.L., Gelman E., & Ramaswamy S. (2008). Airline crew scheduling with time windows and plane-count constraints. *Institute of Industrial Engineers Transactions*. 36(3): 337–348.

Kondo, A. (2008). Delay propagation: Tail-number tracking methodology. Presentation, *Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting*, Washington, D.C.

Law, A. M. (2007). *Simulation modeling and analysis* (4th ed.). New York: McGraw-Hill.

Naval Aviation Energy Conservation Program (Air ENCON). (2014, March 15). Program focus areas. Retrieved from http://airencon. DODlive.mil/

Research and Innovation Technology Administration (RITA) Bureau of Transportation and Statistics. (2014, March 13). Airline on-time statistics. Retrieved from http://apps.bts.gov/xml/ontimesummarystatistics/src/index.xml

Schwartz, M., Blakeley, K., & O'Rourke, R. (2012). *Department of Defense energy initiatives: Background and issues for Congress* (CRS Report No. R42558). Washington, DC: Library of Congress, Congressional Research Service. Retrieved from http://www.fas.org/sgp/crs/natsec/R42558.pdf

Simio reference guide. (2006). Retrieved from http://lyle.smu.edu/emis/docs/Simio/Simio%20Reference%20Guide.pdf

Truckenbrod, D.R. (2010). Estimating the fully burdened cost of fuel for a naval aviation fixed wing platform (Master's thesis, Naval Postgraduate School). Retrieved from https://calhoun.nps.edu/public/bitstream/handle/10945/5336/10Jun_Truckenbrod.pdf?sequence=1

Watters, A. (2013, February 26). Fleet launches aircraft energy-saving initiatives. Naval Air Systems Command Energy Public Affairs. Retrieved from http://www.navy.mil/submit/display.asp?story_id=72352

Weide, O., Ryan D., & Ehrgott M. (2009). An iterative approach to robust and integrated aircraft routing and crew scheduling. Computers and Operations Research. *Institute of Industrial Engineers Transactions*,bc *37*(5): 833–844.

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